SELECTED PORPHYROIDAL AND GRANITIC ROCKS AT TENNANT CREEK, NORTHERN TERRITORY

by

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This thesis contains no material which has been accepted for the award of any other degree or diploma in any University and, to the best of my knowledge and belief, contains no copy or paraphrase of material previously published or written by another person, except where due reference is made in the text of the thesis.

David M.P. Duncan

August 1970

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ABSTRACT.

The Lower Proterozoic sedimentary succession of the Warramunga Group, Northern Territory, Australia is composed essentially of shales, greywackes and conglomerates with minor haematite shales and cherts having an estimated total thickness of 25,000 feet. At Tennant Creek, the lower part of the succession contains conformable horizons, discontinuous lenses, dykes and other isolated bodies of porphyroidal rocks. The rocks show varying degrees of recrystallization and deformation due to an incipient greenschist facies regional metamorphism.

Two porphyroidal bodies have been studied in detail and are generally similar with respect to petrography, mineralogy and chemistry. They contain between 28% and 45% of megacrysts of quartz, potassium feldspar, plagioclase and minor biotite set in recrystallized, dominantly quartzo-feldspathic groundmasses in which relict textural patterns indicate the former presence of close-packed shards, perlitic cracks and possible amygdaloidal patches and identify the porphyroids as volcanic pyroclastics. The Great Western Porphyroid forms a grossly conformable, perhaps composite, horizon at least twelve miles in length and up to 1,500 feet thick and is of ash-flow origin. The Creek Bed Porphyroid is half a mile long, several tens of feet thick and appears to be a dyke.

The shape of the embayments and cavities, extensively developed in the quartz and potassium feldspar megacrysts, appear different from the more regular skeletal or dendritic patterns which are known to result from irregular growth. The close association between curved grain perimeters and embayments suggests that the two are genetically connected and is consistent with weak magmatic corrosion of euhedral grain habits resulting

in rounded corners with associated, selective, internal corrosion producing the embayments and cavities. The presence of Carlsbad and Baveno twinning in the potassium feldspar further supports an igneous derivation for these mineral grains.

Optical and X-ray data indicate that both the potassium feldspar and plagioclase are in a highly-ordered structural condition. In conformity with their structural states, the compositions of the potassium feldspar and plagioclase are consistent with recrystallization at temperatures typical of greenschist facies metamorphic, rather than magmatic, conditions.

The major element compositions of the porphyroids are similar to those of calc-alkaline rhyolites apart from a variable alkali ratio and a low CaO content due to the redistribution of K, Na and Ca, probably as a result of hydrothermal alteration.

The petrographic, mineralogical and chemical similarity of the porphyroids to high-level granites (and selected enclaves) of the neighbouring Tennant Creek Complex suggests a genetic association.

Compositional and structural data on the feldspars are compared throughout the various environments of porphyroid, granite and enclave. The major element composition of the potassium feldspar and the structural states of both the potassium feldspar and the plagioclase are generally similar in the different rock types. This is a result of secondary processes of hydrothermal alteration and/or metamorphic recrystallization, which make it impossible to correlate primary order-disorder and compositional features with environment of occurrence. Delicate, oscillatory zoning preserved in the andesine from the different rock types reveals that the similar plagioclase composition is an original magmatic characteristic. It is concluded that the close similarity of the Rb, Sr and Ba abundances in the potassium feldspar from the various environments is a consequence mainly of the generally similar abundances of these elements in the porphyroid, granite and enclave bulk compositions.

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CHAPTER 1.

INTRODUCTION

This study concerns the nature and origin of certain porphyroidal* rocks occurring in association with Lower Proterozoic sediments of the Warramunga Group - the most important lithological unit in terms of extent, and also the one containing the copper and gold mineralization, in the Tennant Creek area.

The investigation was conducted in the Geology Department University of Tasmania and arose as a result of a Symposium - Syntaphral Tectonics and Diagenesis - held in that Department and at Tennant Creek in 1963. The symposium dealt in part with the nature of the porphyroidal rocks in the Tennant Creek area, two conflicting hypotheses being proposed for their origin.

Summary of existing explanations.

1. In an hypothesis advanced to explain the origin of the

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* The term "porphyroid" is used in a purely descriptive sense in this thesis with no implication of origin. It refers to a rock having the appearance of an igneous porphyry with megacrysts, mainly of quartz or feldspar or both, set in a fine-grained or aphanitic matrix in which rock fragments may also be present.

The term "megacryst" is used in preference to "phenocryst" or "porphyroblast" which have genetic implications.

mineralization in the Tennant Creek Area, Elliston (1965, 1966 and 1968), from the results of field work carried out over a number of years with Geopeko Ltd., considers the porphyroidal rocks to have formed from sediments of the Warramunga Group as a result of segregation, during slumping, of the contained colloidal material into globules and their fracture fragments which subsequently became crystalline during diagenesis and lithification to give rocks having the appearance of igneous porphyries. Following petrographic examination of some of the porphyroidal rocks in thin section, both Nashar (1965) and Fander (1965) support Elliston in suggesting that they are of sedimentary origin.

2. From a petrographical examination of a suite of porphyroidal rocks from Tennant Creek, accompanied by major element compositions of several specimens, Spry (1965) concludes that they are volcanic pyroclastics and lavas.

Porphyroidal rocks recorded by Dunnet and Harding (1965) in the Mount Woodcock map sheet area, immediately to the north of the Tennant Creek map sheet area, are considered, on the results of mapping and some petrography, to be mainly pyroclastics.

Rather than attempt to investigate and map all of the porphyroidal bodies in the Tennant Creek area, it was decided to study two in detail.

Accordingly, a series of four porphyroidal bodies considered by geologists of Geopeko Ltd. to be part of the same porphyroidal horizon - the Great Western Porphyroid - were selected for detailed investigation. These occurrences were chosen because one of them, the Warrego Porphyroid, provided well over 20,000 feet of fresh drill core for examination, an important feature in a region where peneplanation and weathering are advanced. Also, specimens from the Warrego Porphyroid have been used extensively by Elliston to illustrate textural aspects of his hypothesis concerning the derivation of the porphyroidal rocks from sedimentary rocks.

The second porphyroidal body - the Creek Bed Porphyroid - was investigated, as it is one representative of a series of bodies in association with granitic rocks.

In order to appreciate the geological environment of the porphyroidal rocks at Tennant Creek, the geological history of the area is briefly outlined with a more detailed description included of the Warramunga Group sediments.

Detailed descriptions of the selected porphyroidal rocks in terms of field relations, petrography, mineralogy and chemistry are presented in the early chapters. The associated wall rocks of the Warrego Porphyroid are also included in the investigation, as unweathered samples are available from drill core.

The similarity of the mineralogy of these porphyroidal rocks to that of the Tennant Creek Complex has led on to petrographical, mineralogical and chemical investigation of the several granites comprising the complex as exposed in the Station Hill area. As a comprehensive study of the granitic complex was not intended, the sampling of the different members was conducted within the framework of the geological mapping of the Station Hill area by Crohn and Oldershaw (1965).

The petrogenetic aspects of the porphyroidal and granitic rocks are discussed in the final chapter before the conclusions are presented.

The methods and techniques employed in this study are mentioned in the text and outlined in the Appendix. All specimens referred to in this thesis are stored in the Geology Department, University of Tasmania.

CHAPTER 2.

GEOLOGICAL ENVIRONMENT OF THE TENNANT CREEK AREA

The general geology of the Tennant Creek area may be summarized from the information available in reports prepared by Ivanac (1954), Crohn and Oldershaw (1965) and Dunnet and Harding (1965) and is presented in Table I. Further material on certain aspects of the geology is available from work completed by Elliston (1965, 1966 and 1968) and Whittle (1966).

The most important lithological unit in the Tennant Creek area is the Warramunga Group of Lower Proterozoic age. Basement rocks of high metamorphic grade are found in diamond drill holes in the south of the region, quartz-feldspar-garnet gneiss, magnetite schist and amphibolite being recorded. The Warramunga series are overlain with angular unconformity by two lithological units of probable Middle Proterozoic age: the Hayward Creek Beds in the north - a relatively extensive sequence of conglomerates, sandstones, feldspathic sandstones and siltstones and the Rising Sun Formation in the south consisting of conglomerates, sandstones, quartzites and shales. A thin series of Cambrian rocks cover the Warramunga Group rocks to the east of the area and consist of breccias, grits, siltstones, basic or intermediate lava flows and tuffaceous rocks. Superficial Cainozoic deposits consisting mainly of "bulldust", a fine-grained aeolian deposit, and alluvial sands and silts form a thin, obscuring blanket over a large proportion of the region.

TABLE I.

Succession of Geological Events in the Tennant Creek Area

Recent and Tertiary	Aeolian and alluvial deposits, sands and gravels.
Cambrian	Gum Ridge Formation Helen Springs Volcanics.
Middle to Upper Proterozoic	Unconformity Dykes of gabbro, dolerite, diorite and lamprophyre. Quartz veins. Phase 3 deformation, Phase 2 deformation and incipient, regional metamorphism.
Middle Proterozoic	Rising Sun Formation Hayward Creek Beds Unconformity Intrusion of granite, porphyry(?) and quartz veins. Phase 1 deformation.
Lower Proterozoic	Warramunga Group
Archaean	Unconformity Gneiss, schist and amphibolite.

Granitic rocks (e.g. the Tennant Creek Complex) intruded the Warramunga Group rocks during the Middle Proterozoic, but before deposition of the Hayward Creek Beds. This igneous activity may have reached the surface at an earlier time to form a series of acid extrusions fed by vents and fissures within the Warramunga Group rocks. Further igneous activity in the Middle or Upper Proterozoic was responsible for dykes of gabbro, dolerite, diorite and lamprophyre.

At least three phases of deformation have been recognised in the Warramunga Group rocks with an incipient, greenschist facies regional metamorphism being associated with the second phase.

The phase 1 deformation is postulated on the basis of :

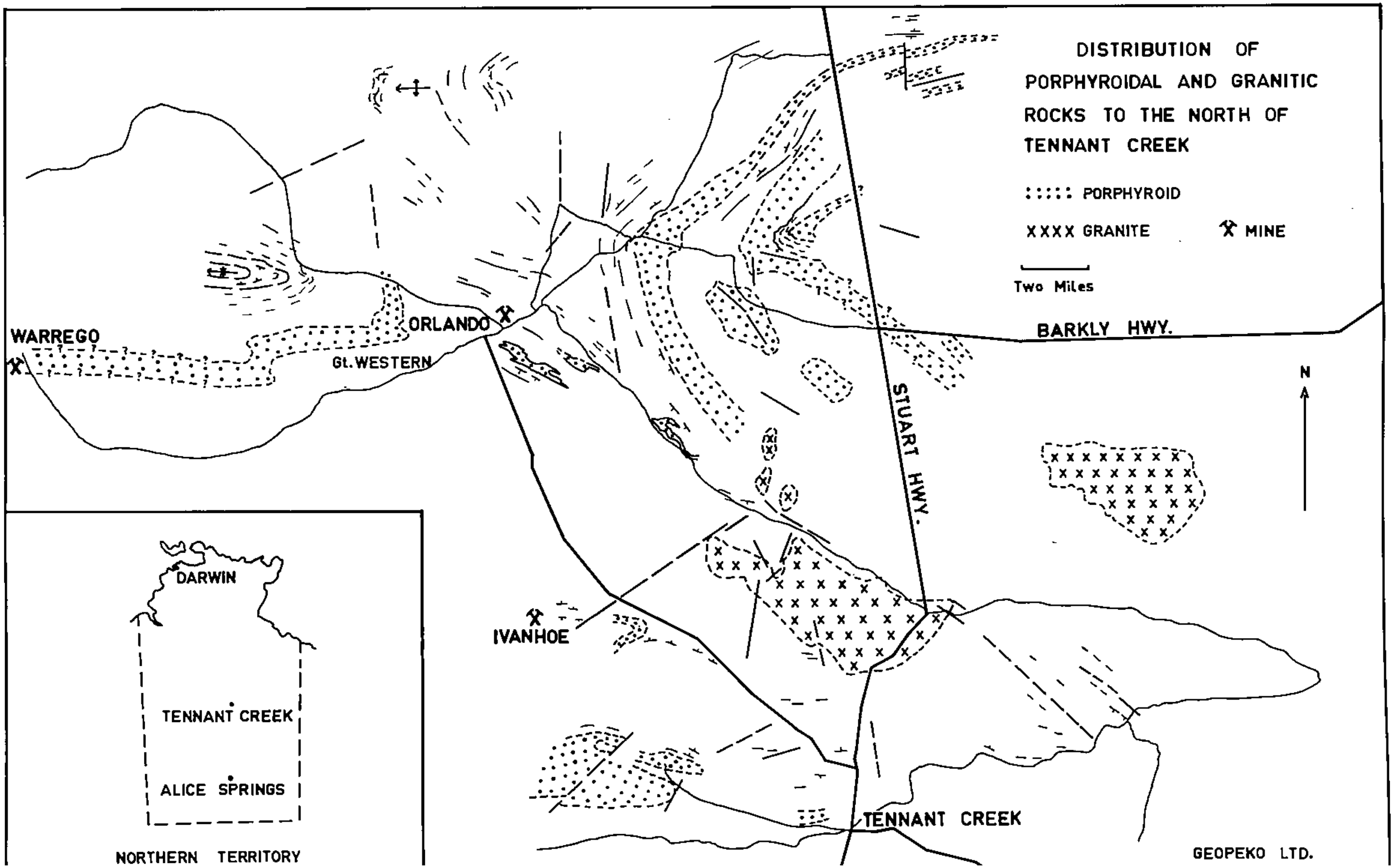
a) the variable direction of plunge of the major fold axes associated with the phase 2 deformation, and

b) the presence of an angular unconformity between the Warramunga Group rocks and the subsequent Middle Proterozoic formations.

The phase 2 deformation is responsible for the main anticl and synclines which fold the lithology of the Warramunga Group and also for the east-west trending, penetrative, regional surf of cleavage, schistosity and foliation which are parallel to the axial surfaces of these folds. The fold axes of the major structures are of variable plunge, either east or west. Minor folds are found in association with this deformation.

Figure 1.

Geological sketch map prepared by Geopeko Ltd. showing the distribution of the main porphyroidal and granitic rocks to the north of Tennant Creek.


DISTRIBUTION OF
PORPHYROIDAL AND GRANITIC
ROCKS TO THE NORTH OF
TENNANT CREEK
:::: PORPHYROID
XXXX GRANITE
MINE
Two Miles
BARKLY HWY.
STUART HWY.
N
WARREGO
ORLANDO
Gt. WESTERN
IVANHOE
TENNANT CREEK
DARWIN
TENNANT CREEK
ALICE SPRINGS
NORTHERN TERRITORY
GEOPEKO LTD.

The phase 3 deformation produced a conjugate system of minor structures such as chevron folds, kink bands and open warps in the regional foliation with subvertical axial surfaces in N.W. - S.E. and N.E. - S.W. orientations. On a larger scale, this deformation appears responsible for a system of regional faults with the N.W. - S.E. direction predominating.

Mineralization of the area resulting in ironstone, gold and sulphide deposits is thought to be connected with basic intrusions (Dunnet and Harding, 1965; Whittle, 1966), with quartz-feldspar porphyry intrusions (Crohn and Oldershaw, 1965), or with porphyroidal rocks (Elliston, 1966).

The Warramunga Group.

The main lithologies present in this group are shales, greywackes, sandstones, siltstones, cherts, haematite shales and conglomerates. The detailed structure and stratigraphic sequence is difficult to establish mainly because of the poor outcrop and the general absence (except for the haematite shale) of marker horizons. Other features complicating correlation of stratigraphic sequences among different areas are probable variations of lithology along strike and the presence of faults of unknown sense and magnitude. Considering the above, along with the fact that neither the base nor the top of the group is exposed, it is impossible to determine the exact thickness of the group which is estimated to be between 12,000 and 25,000 feet (Dunnet and Harding, 1965)..

Simply, the Warramunga Group rocks are divided into three formations which can be summarized thus :-

Blw_3 quartz sandstone, shale and siltstone (possibly in part the equivalent of Blw_2),

Blw_2 greywacke, minor shale and siltstone, haematite shale and pebble beds,

Blw_1 mainly shale and siltstone, minor greywacke.

Features such as graded bedding, micro-crossbedding, load casts, sole markings and small-scale slump structures present in many of the sediments in association with poor sorting, bear evidence of a moderately deep water environment of deposition by turbidity current action, particularly in Blw_2. Pebble beds may be the result of larger scale slumping, and soft-stage intraformational brecciation further testifies to disturbance and instability.

A characteristic feature of the Warramunga Group succession is the occurrence of conformable horizons, discontinuous lenses and other isolated bodies of porphyroidal rocks. These rocks are fairly common in the lower parts of the Warramunga succession, in particular, the Blw_1 formation in which the lithology suggests a shallower subaqueous environment than Blw_2.

CHAPTER 3.

THE GREAT WESTERN PORPHYROID

The Great Western Porphyroid (s.s.*) occurs to the west of the Orlando Mine owned by Peko-Wallsend Ltd. The name applies, in the strict sense, to the quartz-feldspar porphyroid occurring in the group of hills on which Porphyry Hill trig. station rests (Inset A, Fig.2.), one mile to the north of Great Western trig. station.

Other important outcrops of quartz-feldspar porphyroid occur some three miles to the west of the Great Western locality, just to the north of the Black Eye trig. station (Black Eye Porphyroid) and also a further mile to the west in an area referred to in Fig. 2 as Inset B (Inset B Porphyroid

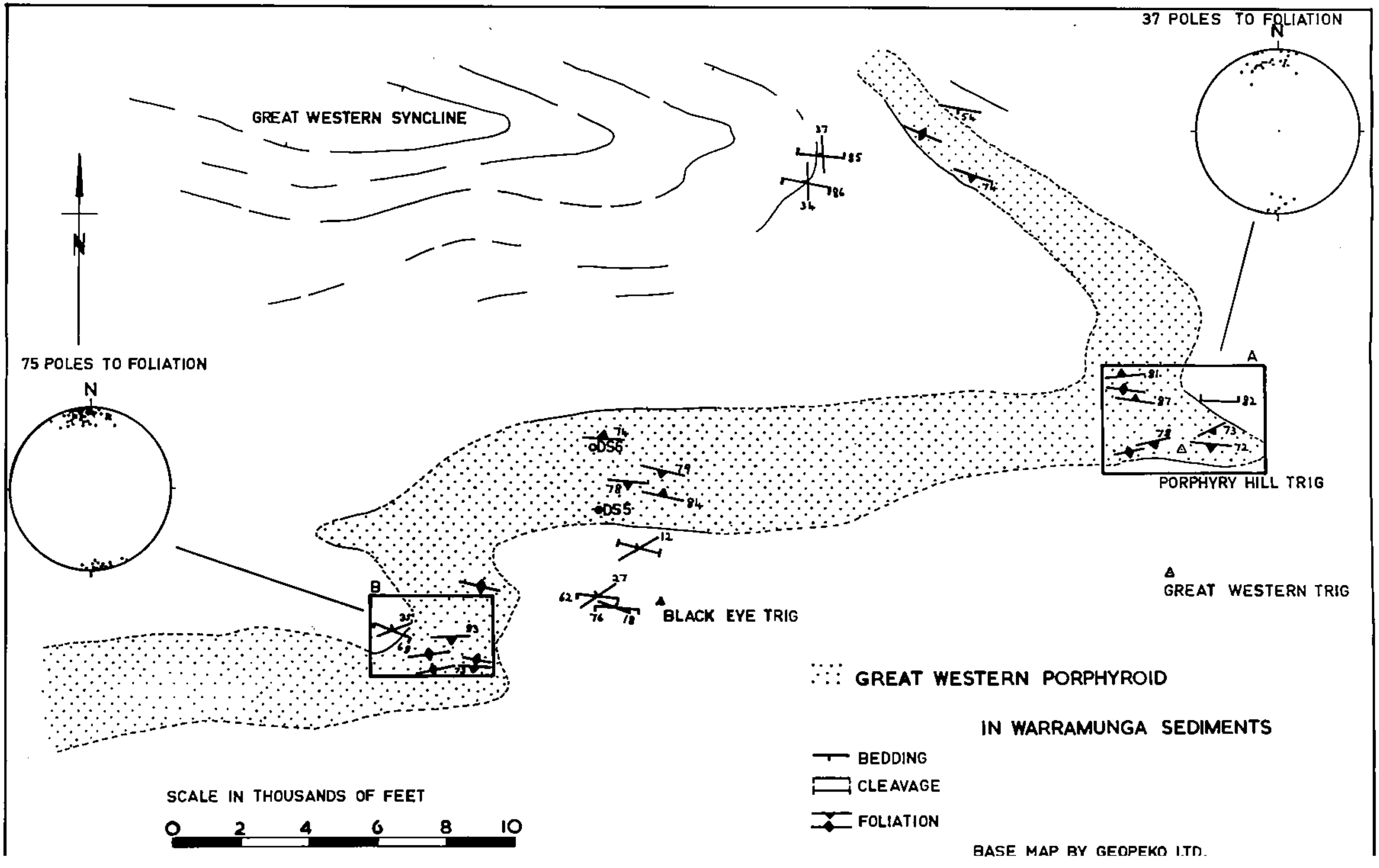
In all these areas, the quartz-feldspar porphyroid is present in low hills generally less than fifty feet high, but prominent on the flat landscape. Other than these occurrences, the outcrop is poor. Mapping by geologists of Geopeko Ltd. suggests that on the basis of ground-level outcrops or the occurrence of characteristic quartz and feldspar detritus the porphyroids are part of a porphyroidal horizon whose extent and shape are given in Fig. 2. (see also Elliston, 1965, page L 17).

On this interpretation, the porphyroidal horizon extends for about six miles and, in shape, reproduces the fold pattern of the Great Western Syncline occurring in the sediments to the

* s.s. - sensu stricto

Figure 2.

Geological sketch map prepared by Geopeko Ltd. showing the outline of the Great Western Porphyroid (s.l.) on which are plotted structural data and the areas investigated in this study.


37 POLES TO FOLIATION
N
GREAT WESTERN SYNCLINE
75 POLES TO FOLIATION
N
A
B
PORPHYRY HILL TRIG
GREAT WESTERN TRIG
BLACK EYE TRIG
DS5
DS6
GREAT WESTERN PORPHYROID
IN WARRAMUNGA SEDIMENTS
BEDDING
CLEAVAGE
FOLIATION
SCALE IN THOUSANDS OF FEET
0 2 4 6 8 10
BASE MAP BY GEOPEKO LTD.

west of the porphyroidal closure. The poor outcrop tends to conceal the structural pattern in the sediments to the east.

Because of the apparent gross conformity of the porphyroid horizon with the bedding of the sediments, it may be considered as a folded sheet-like body.

From surface exposures, it is impossible to gain any information on the attitude of the contacts with depth as the land surface affords little contrast in relief. Considering the width of the outcrop trace with the average dip of the bedding in the immediately adjacent sediments, it is possible to suggest that the southern limb of the horizon is 1,500 feet thick, while the northern limb is thinner at 1,000 feet and is steeper in attitude (Fig. 2).

The foliation in the porphyroidal rocks is parallel to the cleavage in the adjacent sediments (Fig. 2) and has the typical east-west strike and sub-vertical attitude of the regional slaty cleavage. According to Dunnet and Harding (1965) this regional surface, which was synchronous with the regional metamorphism, is parallel to the axial surface of second phase folds of which the Great Western Syncline appears to be a typical macroscopic representative. Hence the foliation in the porphyroids is related to the second fold episode and is a tectonic effect.

The Warrego area is six miles west of the Inset B area directly along strike from the three porphyroidal occurrences already mentioned. The possibility of the Warrego Porphyroid being part of the above porphyroidal horizon, as suggested by Elliston (1965), is based on the results of eight probe holes, drilled by Geopeko Ltd., which penetrated the overburden and sampled the underlying weathered rock (Fig. 3). This suggests a possible minimum length of twelve miles for the porphyroidal horizon.

The Warrego Porphyroid, the Inset B Porphyroid, the Black Eye Porphyroid and the Great Western Porphyroid (s.l.) are collectively referred to as the Great Western Porphyroid (s.l.*) and are described in turn.

1. THE WARREGO AREA.

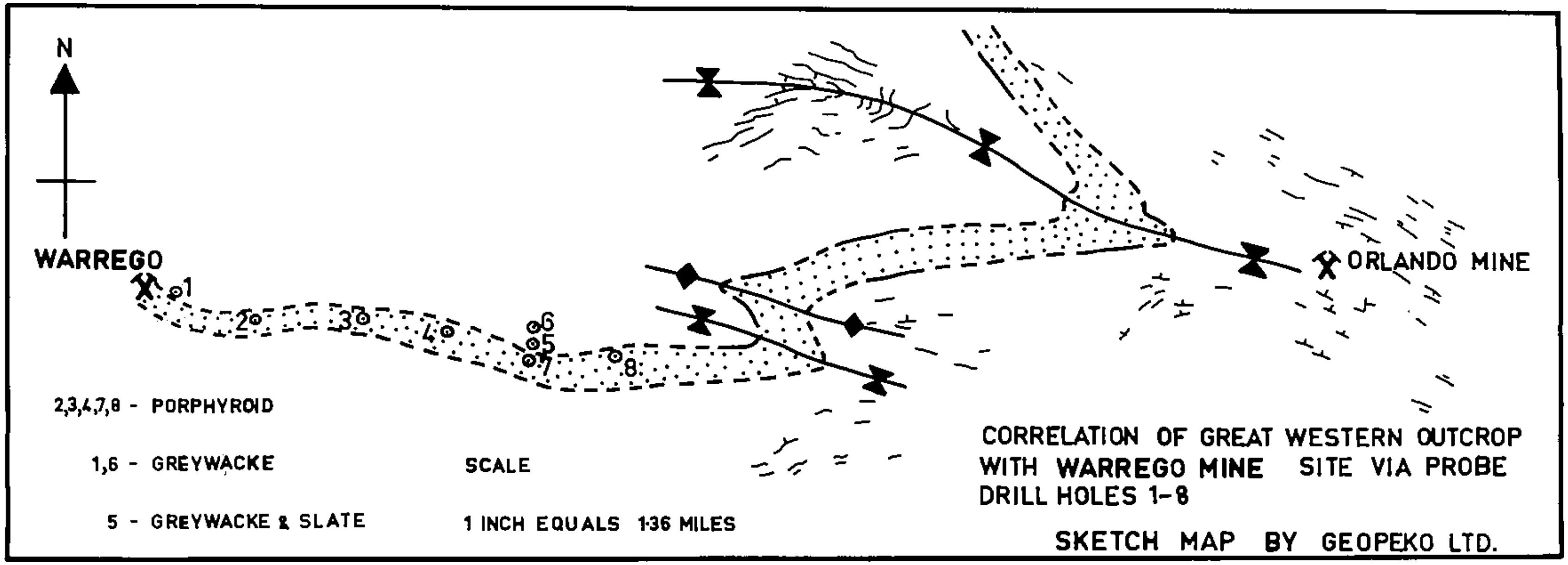
The porphyroids occur in the Warrego Mine (previously known as the Explorer 5 drilling prospect) which is being developed by Peko-Wallsend Ltd. At the time of this investigation, more than 20 diamond drill holes provided well over 20,000 feet of relatively fresh rock, approximately one quarter of which contained quartz-feldspar porphyroid. As there is negligible surface exposure of the porphyroidal rocks in this area because of an overburden consisting mainly of fine-grained eolian deposits, geological details have been compiled entirely from drill hole information.

In broad aspect, up to 700' of quartz-feldspar porphyroid is intersected in the holes and occurs above more than 1,000'

*s.l. - sensu lato

Figure 3.

Geological sketch map prepared by Geopeko Ltd. showing the basis for the correlation of the Warrego Porphyroid with the Great Western Porphyroid (s.l.).


N
WARREGO
1
2
3
4
5
6
7
8
ORLANDO MINE
2,3,4,7,8 - PORPHYROID
1,6 - GREYWACKE
5 - GREYWACKE & SLATE
SCALE
1 INCH EQUALS 1·36 MILES
CORRELATION OF GREAT WESTERN OUTCROP
WITH WARREGO MINE SITE VIA PROBE
DRILL HOLES 1-8
SKETCH MAP BY GEOPEKO LTD.

of relatively fine-grained rocks intercalated with quartz porphyroids. The main contact of the quartz-feldspar body with the underlying rocks appears to trend N.E. - S.W. in strike and dips to the N.E. Numerous thin bodies of lamprophy intrude the whole association.

General relationships of the rocks.

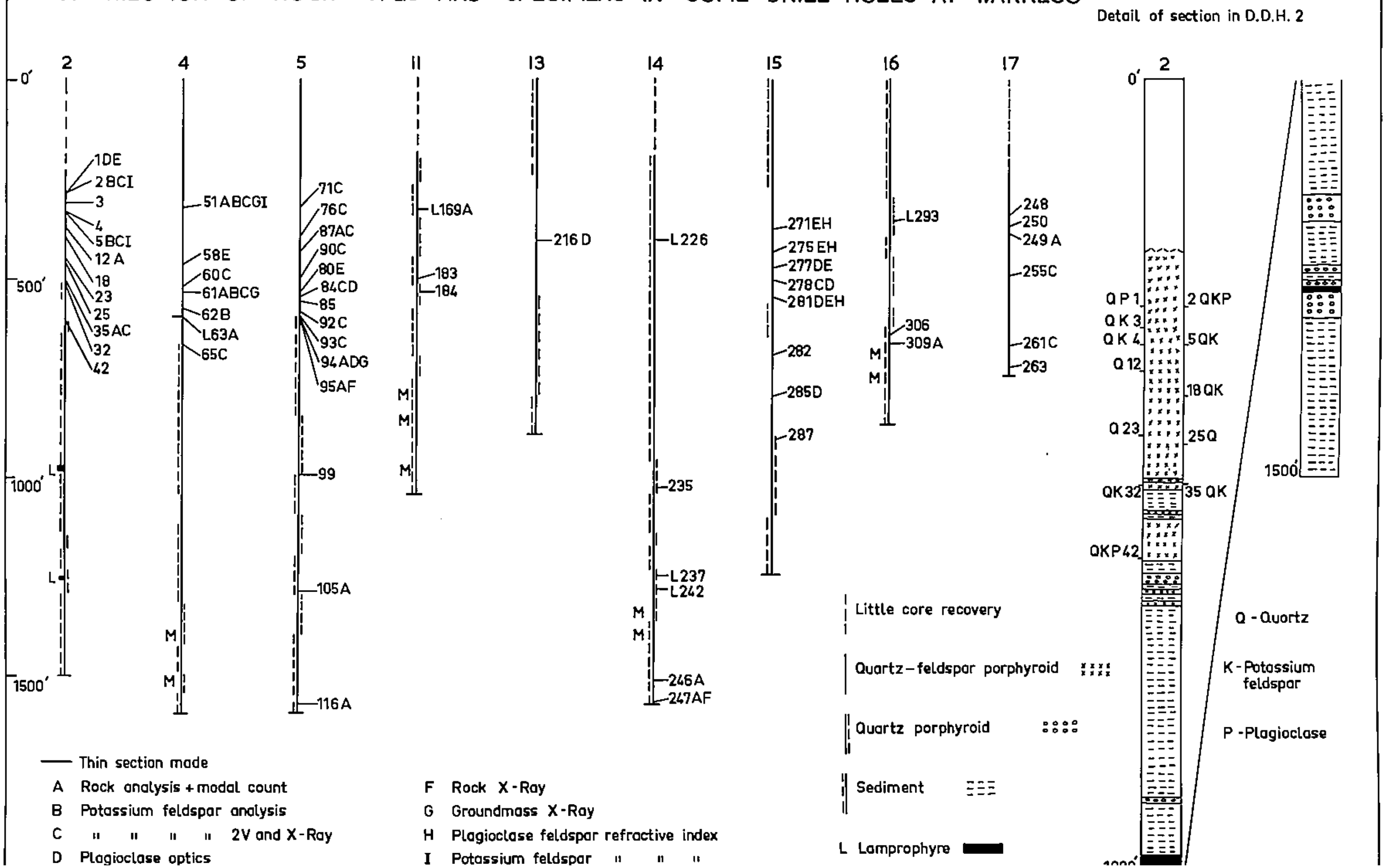
The distribution in depth of the Warrego rocks is illustrated schematically in Fig. 4 using information supplied by nine diamond drill holes. A more detailed section of one of them (D.D.H. 2) is also presented. Of the nine holes, five, (D.D.H. 2, 4, 5, 15 and 17), begin within the main body of the quartz-feldspar porphyroid and after crossing the contact, continue in the underlying rocks, whereas the remaining four holes, (D.D.H. 11, 13, 14 and 16), are located entirely in the rocks structurally below the main contact.

Below the quartz-feldspar porphyroid, a sequence of phyllitic rocks and quartz porphyroids has been recorded for at least 1,000 feet (Fig. 4). The phyllitic rocks contain variations in grain that are not always clearly distinguishable in core section due to the masking effect of greenschist facies metamorphism. In Fig. 4 they are represented in the sections under the general term of "sedimen and range up to 800 feet in thickness.

Figure 4.

Distribution of rock types and selected specimens in some drill holes in the Warrego area.

DISTRIBUTION OF ROCK TYPES AND SPECIMENS IN SOME DRILL HOLES AT WARREGO



Intersections of quartz porphyroid in the drill holes vary from a few inches up to 250 feet (Fig. 4).

Quartz-feldspar porphyroid is encountered below the main body in certain drill holes. The occurrences range from relatively thin bodies of 5 to 50 feet (D.D.H. 2 and 4) to substantial intersections of 300 feet (D.D.H. 13) and are not present in every case (D.D.H. 5 and 14).

Correlation of sections.

Detailed correlation among the various drill holes appears of little significance in the absence of a distinctive marker horizon.

The contacts between the relatively coarse and relatively fine-grained phyllites are not sufficiently distinct to be traced among the drill holes. The quartz porphyroids, although easily recognisable, present no similar number, thickness, or characteristic sequence of bands within the various drill holes. This may indicate that the quartz porphyroids are present as bands of rapidly varying thickness, or as discontinuous lenses, or as both. Their broad, intermixed contacts makes measurement of the exact extent of the bodies more difficult.

The rocks immediately below the main contact of the quartz feldspar porphyroid may consist of either coarse or fine-grained phyllite or quartz porphyroid.

The quartz-feldspar porphyroid recorded below the main contact in some holes may represent discontinuous lower horizo or, if the main contact is irregular in places, may be part of the main body.

The Warrego Porphyroid.

The fresh porphyroid is coloured in varying shades of pal red, grey or green and contains prominent megacrysts of feldspar and quartz set in a groundmass which can be almost massive (Plate 1c) or foliate with green to black micaceous material winding around the megacrysts (Plate 1 a) giving the rocks locally the appearance of augen gneisses. The longer dimensions of the megacrysts tend to lie in the foliation surface as do those of fine-grained, dark coloured rock fragments which occur sporadically throughout the porphyroid. No internal contacts or stratification have been recognised.

PETROGRAPHY.

The minerals present as megacrysts are mainly quartz, potassium feldspar and plagioclase. Various combinations of these minerals produce different megacryst assemblages giving the porphyroid a heterogeneous nature. The assemblages occurring in the rocks selected for detailed study are listed in Table I (a) and provide a representative coverage of all assemblages recorded.

The full assemblage of quartz-potassium feldspar-plagiocl (Group A) occurs fairly frequently and gives way gradually, in

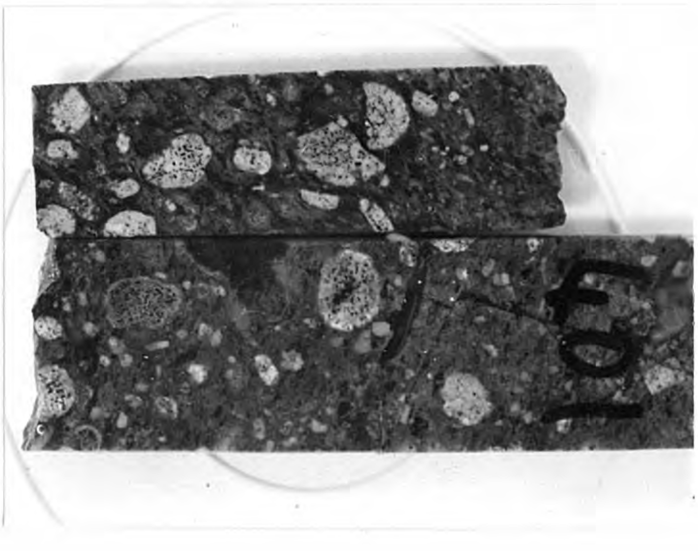
Plate 1 (a)

(Width of field - 4 inches)

Specimens of the Warrego Porphyroid

Plate 1 (b)

(Width of field - 6 inches)



apparent regular manner, to incomplete assemblages which, in some cases, obviously result from alteration of the full assemblage (e.g. specimens 87 and 94, Table I (a)).

As the three minerals in question have characteristic habits (to be described later), it is fairly straightforward to infer the original nature of the pseudomorphs. In cases where incomplete alteration has occurred, the expected correlation between the relict mineral and habit characteristi is always upheld.

Other incomplete assemblages (Group B) are present in which no direct textural evidence of replacement is apparent in terms of relict grain habits (e.g. specimens 35, 12 and 249; Table I (a)). Such assemblages have no obvious pseudomorphs after plagioclase and hence could reflect primary differences in the megacryst associations.

However, plagioclase megacrysts in the complete assemblag show a tendency to be cracked and in part replaced by white mica in the more foliated rocks. Hence, it is probable that indications of the former presence of plagioclase have been completely erased in some of the more foliated rocks (such as specimens 35 and 12 above).

The extent of the pseudomorphing of megacryst minerals varies irregularly from place to place and is more prevalent in some drill holes (e.g. D.D.H. 2 and 17) than in others (e.g. D.D.H. 4, 5 and 15).

It is apparent that the primary assemblage (Group A) is quartz-potassium-plagioclase and that the incomplete (Group B) assemblages (i.e. those lacking any indication of plagioclase) are certainly represented in lesser amount and are probably secondary being derived by alteration of the primary assemblag

TABLE I (a)

Megacryst assemblages in analysed porphyroids.

Group A.

Full assemblage.

Specimens	
51	quartz-potassium feldspar-plagioclase
61	" "
401	" "

Incomplete assemblages - obviously altered from full assemblag

Specimens	
87	quartz-potassium feldspar - (plagioclase almo completely altered to white mica aggregates)
94	quartz - (potassium feldspar completely pseud morphed by plagioclase) - plagioclase.

Group B.

Incomplete assemblages - not obviously altered from full assemblage.

Specimens	
35	quartz-potassium feldspar
12	quartz - (potassium feldspar pseudomorphed completely by white micaceous aggregates)
249	(quartz pseudomorphed by chlorite) - potassiu feldspar.

Small patches and wisps of biotite, chlorite, and white mica are ubiquitous.

Modal analysis of megacrysts.

In order to establish whether or not the megacrysts are present in constant amount within the full assemblage, accura modal counting of quartz, potassium feldspar and plagioclase grains was performed on polished core specimens of rocks selected for analysis (see Appendix I). The results are list in Table 2.

The values obtained have the following ranges in volume percent :-

total megacrysts	28 - 41
potassium feldspar	12 - 20
quartz	9 - 17
plagioclase	3 - 14

From the counting conditions, maximum theoretical varian may be calculated for each mineral constituent (Table II in Appendix I) using the method of Hasofer (1963) and Solomon (1963).

A simple statistical test involving the standard error of the difference between two sample means (Moroney, 1958, p. 220-221) was applied to the following pairs of analyses, specimens 61 and 401 and specimens 61 and 94 (Table III in Appendix I). In all cases, the difference between the sample means is shown to be highly significant.

Apart from secondary variability resulting from the irregular development of alteration throughout the megacrysts,

Table 2.

Modal analyses of megacrysts in porphyroidal rocks at Tennant Creek.

MODAL ANALYSES OF PORPHYROID MEGACRYSTS

Porphyroid Type and Specimen No.	Potassium Feldspar	Quartz	Plagioclase	Total Megacrysts	Groundmass	Remarks
Warrego						
51	13.2	11.3	6.0	30.5	69.5	
61	18.8	9.8	9.4	38.0	62.0	
87	13.8	11.1	3.6	28.5	71.5	
401	12.6	9.1	10.4	32.1	67.9	8.5% white quartz in vesicles
12	-	13.3	-	13.3	86.7	Evidence of replaced potassium feldspar
35	12.8	16.4	-	29.2	70.8	
94	14.7*	12.9	13.2	40.8	59.2	* Plagioclase replacing potassium feldspar entirely
249	19.6	-	-	19.6	80.4	28.4% mafics - some replacing quartz
Black Eye						
477	16.4	9.1	9.3	34.8	65.2	
480	14.4	9.8	7.5	31.7	68.3	
Creek Bed						
(A)						
600	19.4	12.6	13.0	45.0	55.0	
602	18.7†	13.0	12.4	44.1	55.9	† Plagioclase replacing potassium feldspar in part
(B)						
606	16.0+	11.1	14.1	41.2	58.8	+ Plagioclase replacing potassium feldspar entirely

Figures in volume per cent.

modal analysis indicates that, in the full assemblage of potassium feldspar, quartz and plagioclase, the various megacrysts are not present in strictly constant amount althoug they occur within restricted ranges as listed above. The statistics show that the variation is real and not due to variation dependent upon the counting conditions used in the modal analysis.

The Matrix.

In composition, the matrix generally consists of quartz and potassium feldspar with variable quantities of plagioclase biotite, chlorite and white mica.

The crystalline mosaic (0.05 - 0.01 mms. in grain) resulting from the relationship among quartz, potassium feldspar and plagioclase is characterised by the absence of any euhedral outlines. The grains are entirely irregular in shape and exhibit intricate, sutured boundaries.

Both quartz and potassium feldspar have a clear appearanc relative to the turbid plagioclase. Cross-hatch twin patterns suggest microcline, ordinary lamellar twinning indicates plagioclase. X-ray diffraction patterns of the groundmass of various specimens show that the plagioclase content is variable to the extent of being undetectable in some (e.g. specimen 61).

The phyllosilicate minerals, white mica, biotite and chlorite, are generally aligned producing a fabric with a distinct foliation wrapping around the megacrysts with pressure shadows in which the matrix of the rock has recrystallized to a coarser grain.

White mica occurs as thin layers, elongate lenses or individual, minute, stumpy prisms with biotite and chlorite present as minute, irregular patches.

Relict Textures.

Complex arcuate shapes, on a fine scale, are apparent in distribution pattern of the light and dark minerals particular in that of finely-divided white mica.

The patterns indicate that the groundmass of the quartz-feldspar porphyroids consists of a closely-packed arrangement of irregular, fragmental particles whose edges have intricate crescentic or cuspate outlines (Plate 2a, b and c). In general aspect, these patterns are similar to those presented by shards or splinters of volcanic glass found in many well-preserved ashes and tuffs (e.g. Ross and Smith, 1961, Figs. 19, 22).

Hence, it is considered that the groundmass of the porphyroids was originally vitroclastic being composed of shard of volcanic glass which have since recrystallized with the preservation of the original fragmental nature. The state of preservation of these relict textures varies inversely with the degree of development of the foliation in the matrix.

Cellular patterns, outlined by finely-divided white mica

Plate 2 (a)

(width of field - 2 mms; ordinary light)

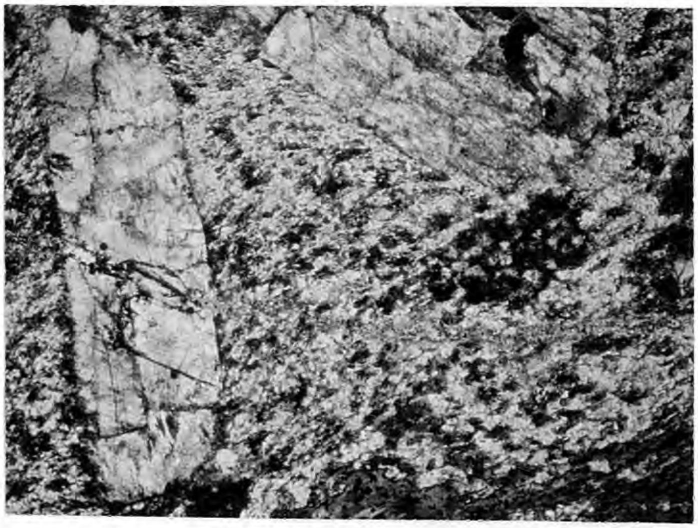
Relict vitroclastic textures in the recrystallized groundmasses of the Warrego Porphyroid.

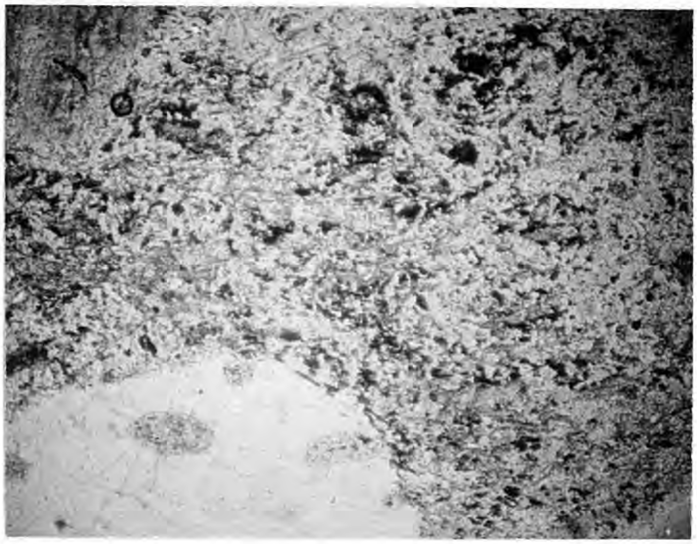
Plate 2 (b)

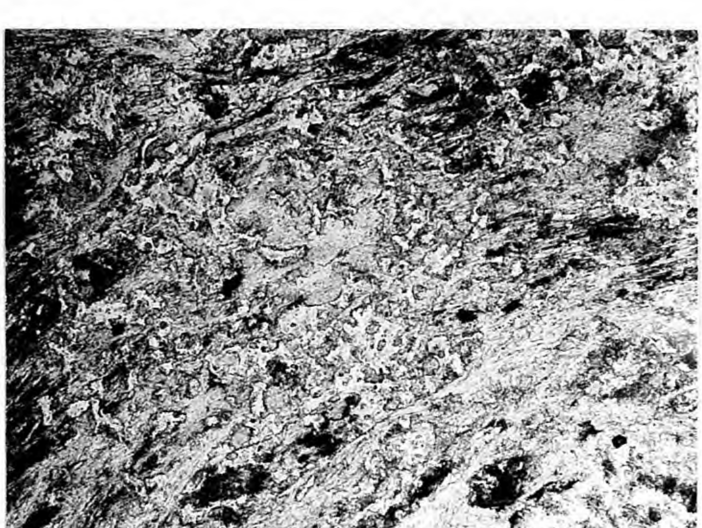
(width of field - 2 mms; ordinary light)

Plate 2 (c)

(X50; ordinary light)







are found only rarely in the groundmass (specimen 401) and are associated with the relict fragmental ash textures (Plate 3a) They are similar in appearance to perlitic crack patterns found in volcanic glass (Ross and Smith, 1961, Fig. 46) where they are attributed to contraction stresses. On this evidence they are considered to be relict perlitic crack patterns providing further indication of the former presence of volcanic glass in the porphyroidal base.

Also found in the fragmental matrix of some rocks (specim 401 and 278) are well-defined ovoid forms generally up to 1mm. long, mainly composed of quartz, occasionally with chlori (Plate 3b and c). A few reach up to 4 cms. in size. Because of their shape and position in a groundmass exhibiting perliti crack patterns, they may be infilled vesicles.

Rock Inclusions.

Dark grey to green rock inclusions occur in the Warrego Porphyroids, generally up to 3 cms. long, crudely tabular in shape and lying in the schistosity surface (e.g. specimens 3, 216 and 215). They are not common and appear to have no systematic distribution in the core sections occurring in both the quartz-feldspar and quartz porphyroids.

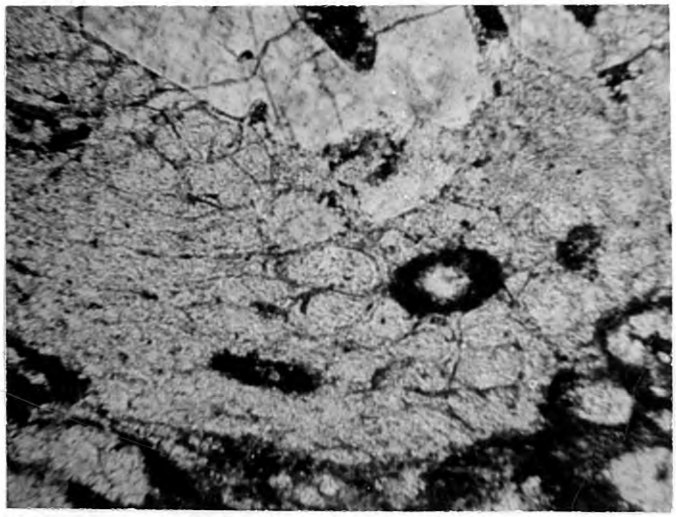
In thin section, they prove to be fine-grained, having a schistosity developed to varying degrees always parallel to that in the host rock.

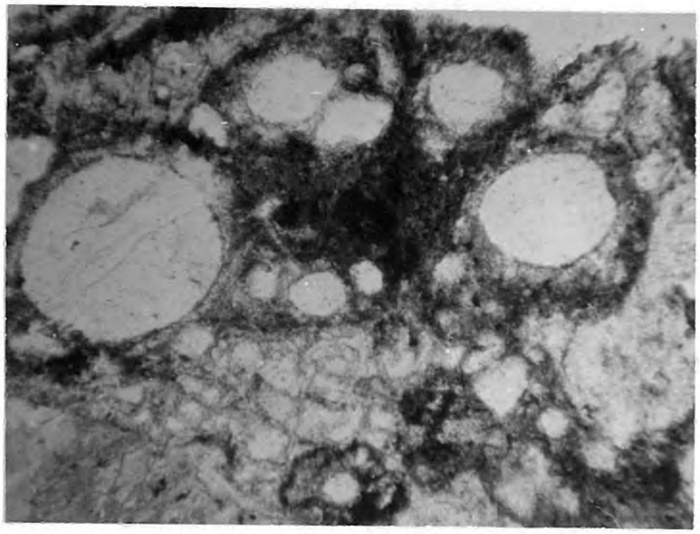
Plate 3 (a) - perlitic crack patterns, fine shards and possible amygdales (width of field - 2 mms; ordinary light).

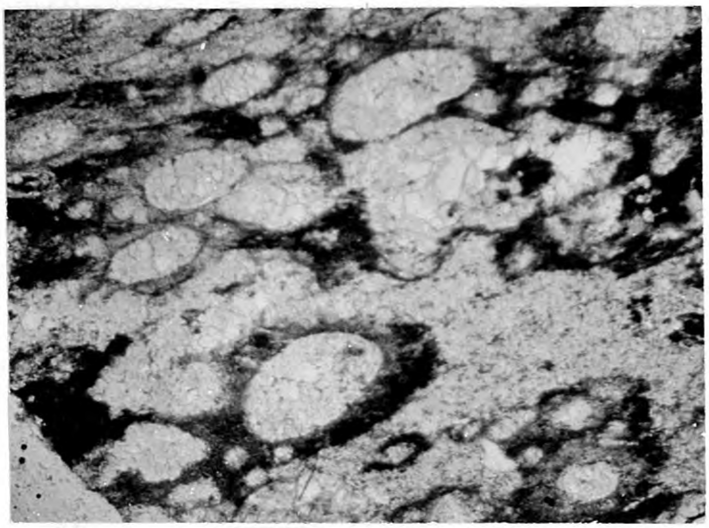
Relict volcanic textures in the recrystallized groundmasses of the Warrego Porphyroid.

Plate 3 (b) - possible amygdales and perlitic crack patterns (width of field - 2 mms; ordinary light).

Plate 3 (c) - possible amygdales (width of field - 3 mms; ordinary light).







The mineralogy is simple, being various combinations of biotite, chlorite, white mica and albite. Quartz is almost always the dominant leucocratic mineral.

In subdued ordinary light, all of the fabrics show the arcuate, fragmental pattern typical of volcanic ash textures which may or may not be flattened, and if so, always in the schistosity direction.

Some inclusions have a coarser grain size in the margins giving a darker rim (e.g. specimen 99).

Also present are other similarly-sized bodies which are much more irregular in shape with extensions running from them along the schistosity (specimens 25 and 25 (a)). These consist mainly of chlorite and their intricate shapes and the fact that they often lie across the schistosity, suggests that they may b replacements rather than inclusions (c.f. Beavon, Fitch and Ras 1961).

MINERALOGY OF MEGACRYST PHASES.

1. POTASSIUM FELDSPAR.

As part of an intensive study of the mineralogy of the porphyroidal rocks, a number of potassium feldspar megacrysts were investigated on an individual basis. Twenty four grains from the Warrego Porphyroid and twelve from the Black Eye Porphyroid were selected and a portion of each grain was made into a thin section for textural and optical study, while the remaining portion was powdered and X-rayed for compositional and structural information.

Texture.

1) Morphology and size.

The size of the potassium feldspar grains is generally between 1 to $2\frac{1}{2}$ cms. In detail, the feldspar megacrysts display a variation in appearance, even within hand specimen. In relative dimensions, the grains range from equant to elongate (length to width ratio of up to 2 : 1).

Quite a number of grains possess regular cross-sections approximating to tabular (Plate 4b), square, elliptical (Plate 6c) or circular (Plate 4c and 6b) shapes. Others are irregular and many of these appear to be fragments of more regularly shaped grains (Plates 5a and 7a). The perimeters of the feldspars may be straight, curved or irregular or, more commonly, may be represented by composite boundaries due to an interplay of the above categories. Tabular sections with approximately straight edges and curved corners are fairl common (Plate 4a). A few grains are idiomorphic, presenting six-sided or square shapes in cross-section (Plates 4b and 7a) Others have completely irregular perimeters (Plate 5b).

2) Cavities and embayments.

Without exception, the megacrysts display a remarkable abundance of internal cavities and embayed edges, producing a sieved or honey-combed aspect easily visible in hand specimens due to dark, included material (described later).

Plate 4 (a)

(width of field - one inch; ordinary light).

Potassium feldspar megacrysts in the

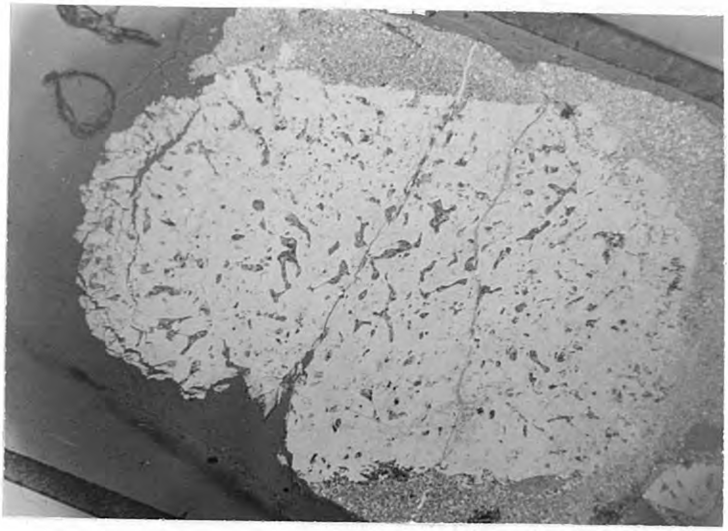
Warrego Porphyroid.

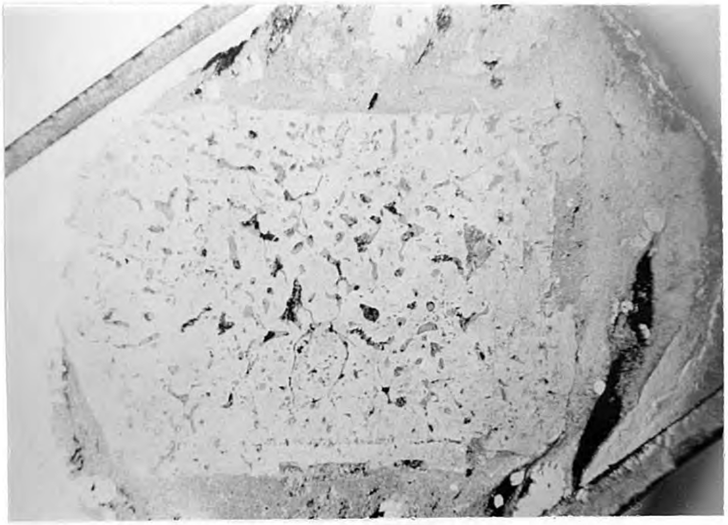
Plate 4 (b)

(as above).

Plate 4 (c)

(width of field - one inch; crossed polars).





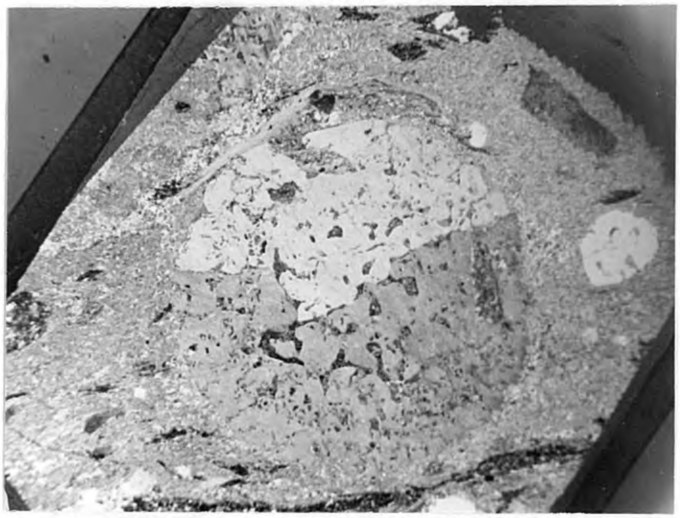


Plate 5 (a)

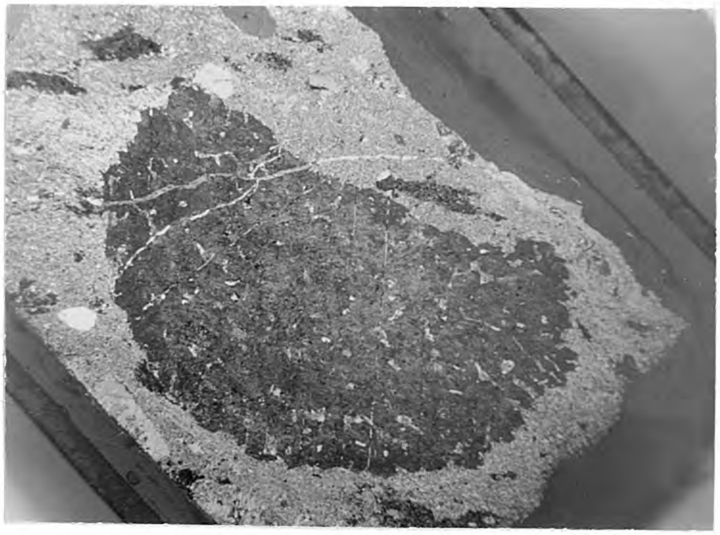
(width of field - one inch; crossed polars).

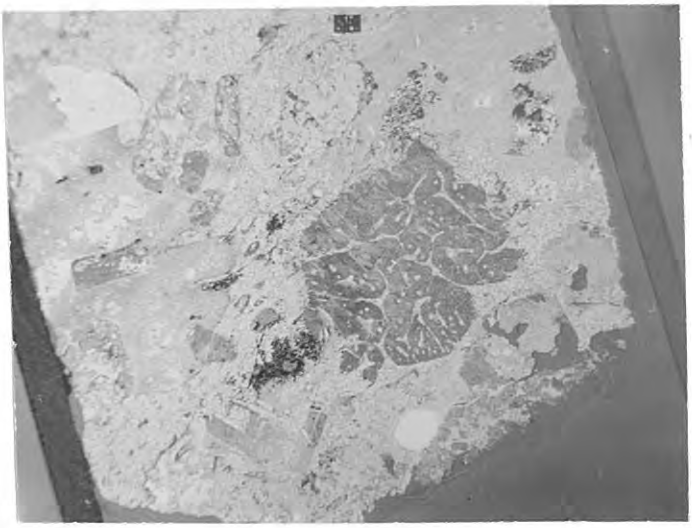
Potassium feldspar megacrysts in the Warrégo Porphyroid.

Plate 5 (b)

(as above).

Plate 5 (c) - potassium feldspar replaced by plagioclase (as above).





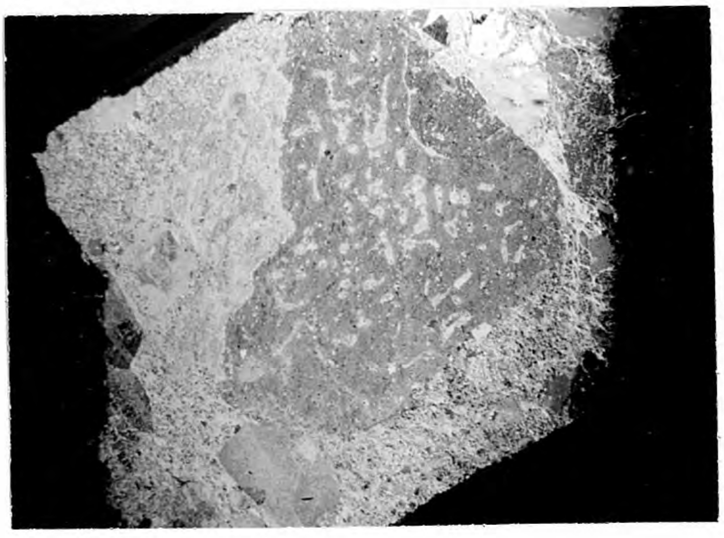


Plate 6 (a)

(width of field - one inch)

Potassium feldspar megacrysts in core specimens of the Warrego Porphyroid.

Plate 6 (b)

(main scale units - 1/4 inch).

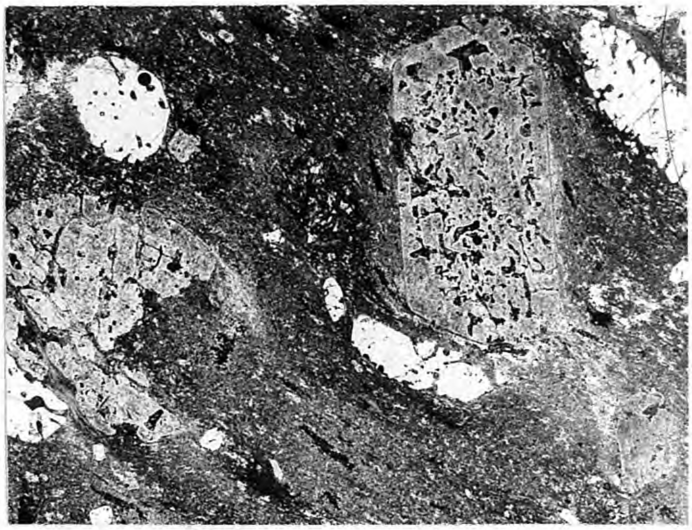
Plate 6 (c)

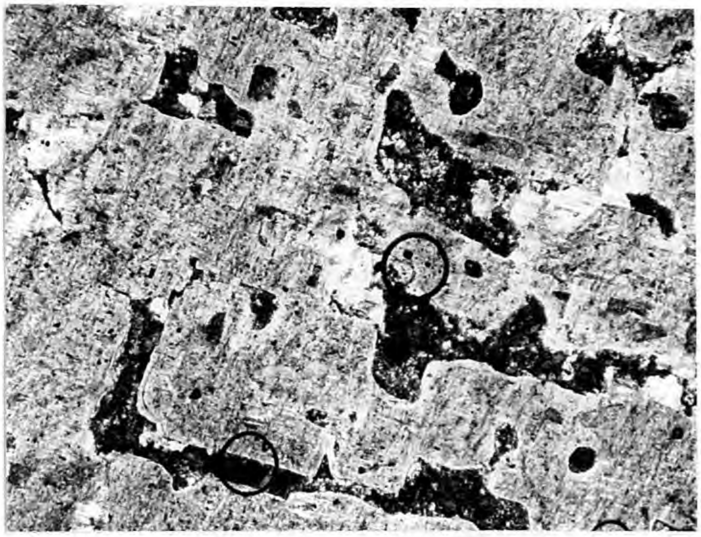
(main scale units - 1/8 inch).

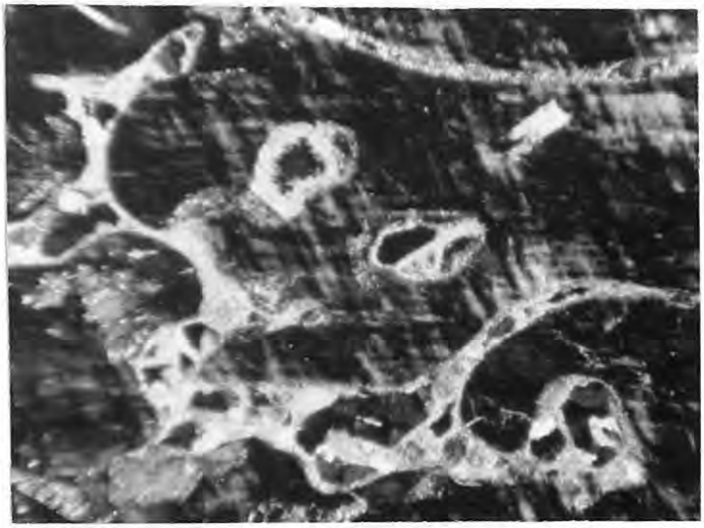
Plate 7 (a) - embayed megacrysts of potassium feldspar, quartz and ferromagnesian minerals in the Black Eye Porphyroid (X4; ordinary light).

Plate 7 (b) - detail of cavities in potassium feldspar, Warrego Porphyroid (width of field - 2 mms; crossed polars).

Plate 7 (c) - as above.







a) Size.

The longer dimensions of most of the cavities are in the range 0.5 to 4 mms. The embayment channels may reach as far a 10 to 15 mms. into the interior of grains. Both the embayment and cavities are less than 0.5 mms. in width.

b) Shape.

The embayment channels form long, vermicular lobes which frequently open into irregular areas indistinguishable in shap from the enclosed cavities, whose edges are made up of combina tions of cusps, generally convex towards the cavities, sometim with accompanying straight sections giving many of the cavitie a runiform aspect (Plates 4, 5, 6 and 7).

Where straight edges do occur, they are generally paralle to one or other of the two main cleavage directions in the hos potassium feldspar. This relationship implies some degree of structural control of the cavity edges by the host mineral. Whereas, in some cases, this control appears relatively well expressed (Plate 7b), in other cases it is less obvious (Plate 7c).

c) Distribution and orientation.

The development of these features varies from crystal to crystal. Within grains, the distribution may be uniform, irregular or, in some cases, approximate to a crude zonal arrangement.

In many grains, the marginal embayments and cavities are only vaguely defined, while in the core, the cavities tend to be larger and more distinct (Plate 4).

These grains in which the marginal features are also distinct, generally show zonal characteristics in the distribution pattern of their cavities and embayments.

Narrow, embayment channels running at high angles to the grain edges, traverse the rim which is about 1 to 3 mms. wide. This relationship is responsible for the noticeable radial distribution of the channels in the margins of many of the grains (Plate 6a and b).

The inner edge of the rim is marked by the opening out of the narrow embayment channels into shapes, indistinguishabl from those of the cavities well within the core, which occur concentrated in a concentric zone for the most part parallel to the exterior margins of unfractured grains (Plate 6 a and b In thick sections, it is sometimes possible to trace, within the body of a grain, connections between neighbouring vermicul cavities and, in exceptional cases, to observe a connection eventually reaching a grain exterior.

This relationship suggests that the cavities and embaymen represent sections through a three dimensional network of sinu interconnecting tubes which ultimately have outlets to the exteriors of the grains.

A close association is apparent between curved grain edge and embayments. Also zones with a high concentration of cavities are best developed inside curved, embayed edges, whereas inside straight edges, they may be vague and discontinuous (Plate 6 a).

A few instances are noted where, in their pattern of cavities, some grains have the appearance of isolated cores which do not possess rims (Plate 6 c).

In some cases, the cavities and embayments show some degree of preferred orientation in the cleavage directions of the host feldspar (Plate 6 b) which consequently must be exerting some structural control on the orientation of these features. Also in this context, the cavities and embayment channels show a preference to follow the composition surfaces of simple twins, no matter how irregular, and can be seen branching from, but never cutting directly across, the twin surfaces (Plate 4c).

d) Content.

The material occurring in the embayments and cavities of the potassium feldspar consists of those minerals present in the groundmass of the porphyroids. They are quartz, feldspar, biotite, chlorite, white mica, epidote, apatite and opaque minerals. They show a range in grain size from 0.2 mms. down to a finely divided condition just resovable microscopically. No amorphous or cryptocrystalline material is present.

Although it is normal to find mafic and leucocratic minera together in the same cavity, there is a perceptible concentrat of the ferromagnesian minerals in those cavities in the cores of the megacrysts (Plate 4 b).

e) Textures.

Generally, the minerals within the embayments and cavitie of the potassium feldspar occur in combination as granular aggregates of irregular distribution.

However, in certain cases, distinctive, textural patterns are evident in the distribution of the mineralogy and are of some significance.

Cellular patterns are found in the embayment channels of feldspar (and, as described, in the groundmass of the rock) of specimen 401. These patterns, which are of rare occurrence in these rocks, appear as clusters of irregular cells (Plate 9 outlined in minute, finely-divided granules probably of white mica on a background of quartz and feldspar. In shape they ar similar to the perlitic crack patterns developed by shrinkage in volcanic glass (Ross and Smith, 1961). Hence they are considered to be relict textures inferring the former presence of volcanic glass, which has subsequently recrystallized.

Globular patterns are slightly more common than cellular patterns and are recorded in several specimens where they are expressed in differing mineral combinations.

Plate 8 (a)

(width of field - 2 mms; ordinary light).

Relict bubble textures in feldspar megacryst cavities.

Plate 8 (b)

(as above).

Plate 8 (c)

(as above).

Plate 9 (a) - relict bubble textures.
(width of field - 2 mms; ordinary light).

Relict textures in feldspar megacryst cavities.

Plate 9 (b) - relict perlitic crack patterns in megacryst embayment (width of field - 2 mms; ordinary light).

Small (up to 0.6 mm.), smooth ovoid aggregates of biotite or chlorite laths are set in a finely-divided white mica matri in some of the inclusion cavities of specimen 5.

In specimens 32 and 35, the cavities contain circular, elliptical, arcuate and irregular patterns of minute granules mainly of white mica set against a mosaic of interlocking quartz grains. Little ferromagnesian material occurs in these inclusions. The thin, hair-like arcs which outline many of these patterns cut across the grain boundaries of the quartz mosaic.

By far the most abundant occurrence of textures of this type is recorded in the megacrysts of specimen 94 where the shapes are well-defined. Many show a close approach to circular outlines ranging from 0.2 to 0.6 mm. in diameter (Plates 8 a and b). Some elongate globules (up to 1.5 mm. lon can have tapered, pinched or waisted shapes where the walls of the cavities provide a constriction, (Plates 8 c and 9 a).

Up to six globules have been recorded in the same cavity (Plate 8 b).

These textures may have cores of biotite or chlorite aggregates, white mica granules, or simply quartz. When mafic minerals occur, they are confined to the cores, rarely appearir elsewhere in the cavity and are surrounded by a zone of finely-divided white mica. The outlines of the globules are expressec in one or two enveloping trails of white mica granules. Quartz and feldspar grains generally form the background mosaic of the cavities.

In their shape and occurrence in the cavities within mineral grains, the globular patterns are very similar to bubbles associated with fluid inclusions. The characteristic presence of a number of globules (up to at least six) containe in the same cavity is typical of bubbles accompanying inclusio of silicate glass which occur in the minerals of many volcanic and some sub-volcanic, rocks (see Tuttle, 1952b).

Taken in conjunction with relict perlitic crack patterns in the embayments of the feldspars, the numerous relict bubble shapes infer the former presence of a silicate melt, since solidified and recrystallized, whose relatively high viscosit (and probable rapid rate of cooling) prevented the coalescence of adjacent bubbles (Yermakov, 1965, p.19).

In accord with most recorded instances in the literature (Yermakov, 1965), the bubbles were probably originally gaseous However, Roedder and Coombs (1967) have reported certain inclusions in the minerals of some peralkaline granite blocks which infer the former presence of bubbles of saline fluid in silicate magma.

Spherulitic textures.

On a few occasions, spherulites of potassium feldspar, about 0.4 mms. in size, are found in the cavities.

3) Twinning.

a) Cross-hatched twinning.

In the course of universal stage measurements, most grains showed cross-hatching when suitably oriented. The twinning is patchy, on a fine scale and can have slightly different orientations in adjacent domains.

b) Simple twinning.

During the examination of the large feldspar megacrysts, composite grains were found. Optical measurement (Appendix II on the universal stage reveals that most of the composite grains have their sub-individuals related by twinning, although a few may approximate to parallel growths. The twin laws recorded are Carlsbad and Baveno, with the former being the more common (Table VIII, Appendix II).

The Carlsbad twins consist of two sub-individuals joined along a composition surface, the trace of which is characteristically irregular and sinuous (Plate 4 c).

The Baveno combinations generally comprise three sub-individuals also with irregular composition surfaces.

In general, the habits of the twinned grains show little evidence of re-entrant angles.

4) Associated plagioclase.

A few potassium feldspar megacrysts are seen to have single, euhedral plagioclase inclusions while others possess rare, discontinuous plagioclase rims (specimens 401 and 480).

Optical determination.

1) Optic axial angle.

The optic axial angles, 2Vx, of all potassium feldspar megacrysts from the rock samples investigated fall within the range of 60^{o} - 90^{0} (for measurement procedure, see Appendix II

Variation within individual megacrysts.

An average of five optic angle measurements were recorded on each grain, the range and average value being indicated in Table 3 and Fig. 5. It is evident that some grains show an internal variation in the value of 2Vx (i.e. they show a spread in values greater than the precision of the method which is $\pm 2^{o}$). The values within each grain can be different in close proximity and, bearing in mind the limited number of observations from each grain, there is no evidence that the values towards the perimeters are consistently different from those in the core.

2) Orientation of the optical indicatrix.

No attempts were made to define the exact orientation of the optical indicatrices in the megacrysts, as to attain sufficient accuracy for the readings to be of any value, requires special thick, goniometrically orientated, mineral sections (Marfunin, 1962).

However, during the investigation of twinning in the potassium feldspars, it was confirmed that the optic axial planes are approximately perpendicular to (010) and that the

Table 3.

Optical and X-ray data on individual potassium feldspar megacrysts from rocks at Tennant Creek.

POTASSIUM FELDSPAR MEGACRYSTS

WARREGO

Megacryst Nos.	Range 2Vx°	Mean 2Vx°	Δ	UNHEATED Or mole %		Ab + An mole %	HEATED Ab + An mole %
5	71-76	74	0.86	96.0	96, 96	4.0	8.0
61 (a)	69-73	71	0.86	99.0	100, 98	1.0	19.0
61 (b)	69-76	73^{e}	0.87	95.8	95, 96.5	4.2	13.5
60	69-77	71	0.87	96.0	96, 96	4.0	16.0
90 (a)	74-81	78	0.89	98.3	98.5, 98	1.7	16.0
90 (b)	-	-	0.88	97.2	*	2.8	14.5
76	71-79	76^{e}	0.89	98.8	99.5, 98	1.2	7.7
401(a)	78-80	79	0.89	96.3†	96, 96.5	3.7	5.5
92 (a)	-	-	0.79	98.0	98, 98	2.0	9.7
92 (b)	73-76	75	0.78	99.8	99.5, 100	0.2	12.3
87	71-76	73	0.78	97†		3	15.5
261	67-72	71^{e}	0.76	95.8	96.5, 95	4.2	9.7
84	69-75	73	0.91	97.5	97, 98	2.5	21.5
278	73-75	74	0.77	100	100, 100(+)	0	17.0
2	74-76	75	0.86	97.0	97, 97	3.0	10.2
71	72-81	76^{e}	0.94	98.0	98, 98	2.0	17.2
329 (a)	67-77	72^{e}	0-0.66	99.8	99.5, 100	0.2	13.0
329 (b)	71-83	77^{e}	0-0.75	100	99.5, 100(+)	0	15.7
35	72-74	72	0-0.77	100†	100, 100	0	-
255	67-79	71^{e}	0-0.92	97.8	98.5, 97	2.2	8.2
5T	74-81	76	0-0.78	97.0	97, 97	3.0	1.0
65	74-81	79^{e}	0-0.71	100	100, 100	0	13.2
51	68-73	71	0-0.89	97.8	97, 98.5	2.2	18.2
93	70-77	73	0-0.67	100	100, 100	0	10.7

BLACK EYE

Megacryst Nos.	Range 2Vx°	Mean 2Vx°	Δ	UNHEATED Or mole %		Ab + An mole %	HEATED Ab + An mole %
477 (a)	69-83	77	0.91	95.8	95, 96.5	4.2	17.5
477 (b)	67-83	75^{e}	0.89	97.5	97, 98	2.5	19.7
491 (b)	73-82	76	0.90	99.3	98.5, 100	0.7	15.0
479 (a) 1	74-82	79^{e}	0.89	96.8	96.5, 97	3.2	20.2
479 (a) 2	75	75	-	-	-	-	-
479 (a) 3	75-77	76	0.90	99.5	99.5, 99.5	0.5	15.0
480 (a)	68-71	70	0.91	96.8	96.5, 97	3.2	13.5
480 (b)	68-79	72	0.90	98.5	98.5, 98.5	1.5	15.7
480 (c) 1	79-80	79	0.89	98.0	98, 98	2.0	15.2
480 (c) 2	77-83	80	0.89	97.0	97, 97	3.0	20.2
481	64-73	70	-	-	-	-	-
483	71-82	76	-	-	-	-	-
				CREEK BED			
602 (a)	77-80	78	0.83	96.5	96.5, 96.5	3.5	33.0
				MIRARRMINA			
8A (a)	55-67	61	0-0.80	97.8	97, 98.5	2.2	19.7
8A (b)	62-65	64^{e}	0-0.82	97.8	97, 98.5	2.2	23.2
A1	60-66	64	-	-	-	-	-

x minor granite

e 2V measured using extinction techniques

* 6 runs to estimate reproducibility

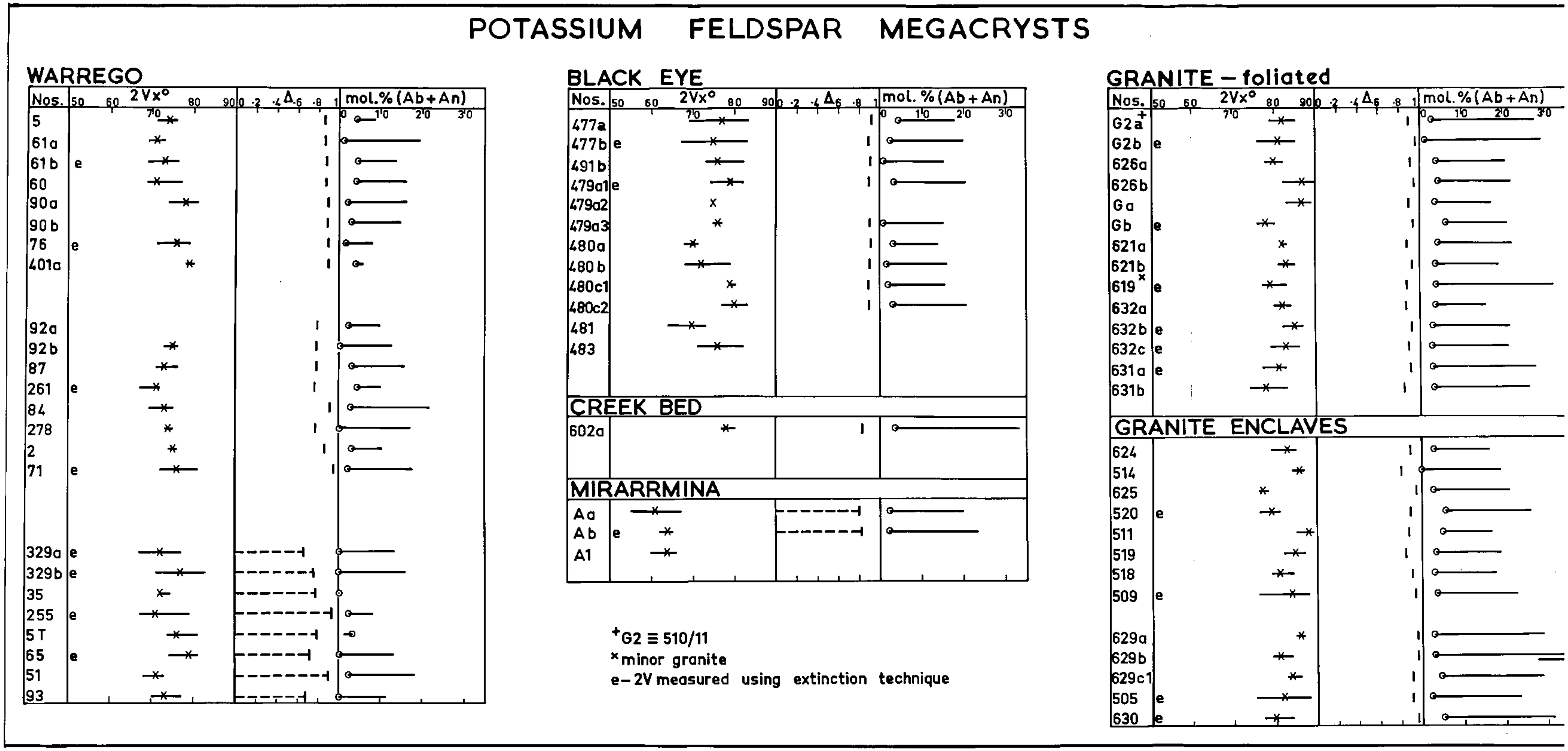
† interference by quartz peak

GRANITE - foliated

Megacryst Nos.	Range 2Vx°	Mean 2Vx°	Δ	UNHEATED Or mole %		Ab + An mole %	HEATEI Ab + A mole %
510/11 (a)	79-85	82	0.90	97.0	97, 97	3.0	27.5
510/11 (b)	76-85	81^{e}	0.96	98.8	99, 98.5	1.2	29.0
626 (a)	78-82	80	0.91	96.0	96.5, 95.5	4.0	20.5
626 (b)	82-90	87	0.95	95.3	95, 95.5	4.7	21.2
G (a)	83-89	87	0.90	96.0	96, 96	4.0	17.2
G (b)	76-80	78^{e}	0.94	93.5	94, 93	6.5	21.2
621 (a)	82-83	82	0.88	95.5	95.5, 95.5	4.5	22.2
621 (b)	81-85	83	0.93	96.0	96, 96	4.0	19.2
619	77-83	79^{e}	0.88	96.0	96, 96	4.0	32.2
632 (a)	80-84	82	0.87	96.5	96, 97	3.5	15.7
632 (b)	82-87	85^{e}	0.93	96.8	96.5, 97	3.2	21.5
632 (c)	79-86	83^{e}	0.89	96.5	96, 97	3.5	21.0
631 (a)	77-83	81^{e}	0.91	97.0	97, 97	3.0	28.0
631 (b)	74-83	78	0.85	96.8	96.5, 97	3.2	26.0
				GRANITE ENCLAVE			
624	79-85	83	0.90	97.0	97, 97	3.0	16.2
514	84-87	86	0.81	100(+)	100(+), 100(+)	0	18.7
625	76-78	77	0.95	97.0	97, 97	3.0	21.0
520	76-81	79^{e}	0.90	94.3	94.5, 94	5.7	26.0
511	85-89	88	0.88	94.8	94.5, 95	5.2	16.7
519	82-87	85	0.85	96.5	96, 97	3.5	18.7
518	79-84	81	0.91	96.8†	96.5, 97	3.2	17.5
509	76-88	84^{e}	0.94	96.3	96, 96.5	3.7	22.7
629 (a)	85-87	86	0.96	97.0†	96, 98	3.0	29.0
629 (b)	79-84	81	0.96	97†	97	3.0	42.5
629 (c)	83-86	84	0.91	95.3†	96, 94.5	4.7	28.5
505	75-88	82^{e}	0.91	97.8†	97, 98.5	2.2	23.2
630	77-84	80^{e}	0.96	94.8†	94.5, 95	5.2	31.2

Figure 5.

Diagrammatic representation of optical and X-ray measurements carried out on individual potassium feldspar megacrysts from rocks at Tennant Creek.


POTASSIUM FELDSPAR MEGACRYSTS
WARREGO
Nos.
2Vx°
50 60 70 80 90
0 ·2 ·4 Δ6 ·8 1
mol.% (Ab+An)
0 10 20 30
5
61a
61b e
60
90a
90b
76 e
401a
92a
92b
87
261 e
84
278
2
71 e
329a e
329b e
35
255 e
5T
65 e
51
93
BLACK EYE
477a
477b e
491b
479a1 e
479a2
479a3
480a
480b
480c1
480c2
481
483
CREEK BED
602a
MIRARRMINA
Aa
Ab e
A1
GRANITE – foliated
G2a+
G2b e
626a
626b
Ga
Gb e
621a
621b
619× e
632a
632b e
632c e
631a e
631b
GRANITE ENCLAVES
624
514
625
520 e
511
519
518
509 e
629a
629b
629c1
505 e
630 e
+G2 ≡ 510/11
×minor granite
e– 2V measured using extinction technique

angle $Z \wedge \perp (010)$, if not accurately definable in thin section, has a distinct, small value (Table VIII, Appendix II) proving that at least parts of the grains have triclinic symmetry with respect to optics.

3) Refractive index.

The refractive index, Nx, was checked on a few megacryst and the values are listed in Table IX (Appendix II). As anticipated, there is little variation in this parameter, the values 1.520 - 1.522 being consistent with those of potassium-rich feldspars (Tuttle, 1952a).

X-ray determination.

1) Obliquity.

Each megacryst selected from study was X-rayed in powder form on a diffractometer and the obliquity calculated from the separations of the X-ray spectra (131) and ($1\bar{3}1$) following Goldsmith and Laves (1954) (see Appendix II).

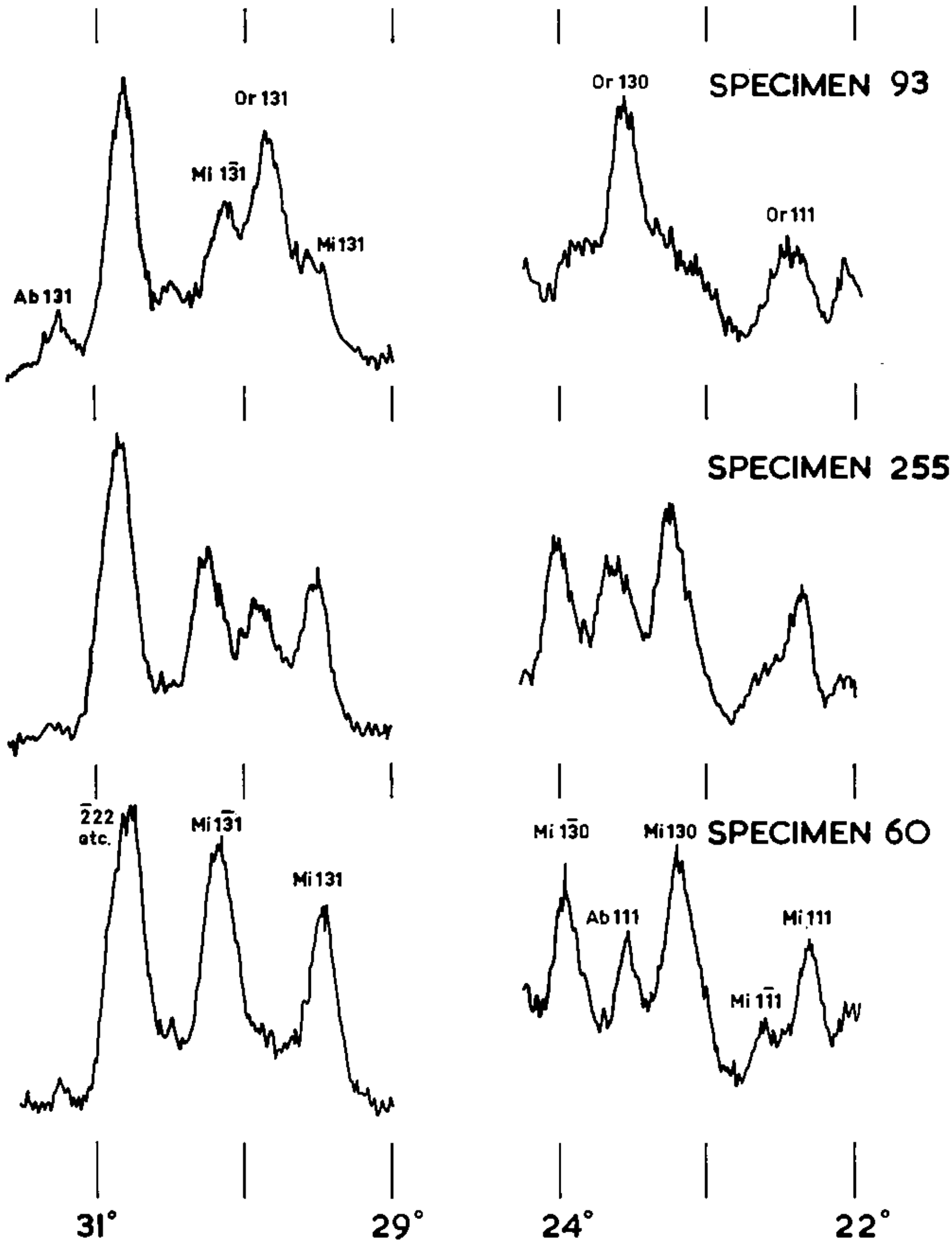
As seen from Table 3 and Fig. 5, the potassium feldspars from the Black Eye Porphyroid tend to have the high obliquitie (0.89 - 0.91) of near-maximum microcline. However, significan variations are evident in the obliquities of some of the potassium feldspar megacrysts in the Warrego Porphyroid, and accordingly on the basis of their diffraction patterns, the grains are listed in three groups.

Group 1. The first group of grains in Table 3 have obliquities (0.86 - 0.89) closely similar to those just reported for the Black Eye potassium feldspars. The range of values in each occurrence are within the limits of precision of the method ($\pm$ 0.02). The diffractometer traces of this group are represented by that of specimen 60 in Fig. 6 in which the triclinicity of the grains is clear seen in the separation of the X-ray peaks 13 1$\bar{3}$1, 130 and 1$\bar{3}$0 and III and I$\bar{\text{I}}$I.

Group 2. The megacrysts of this intermediate group record traces of zero to low obliquities in their X-ray patterns and have a spread in their maximum obliquities approaching that of Group 3.

Group 3. The last group of megacrysts in Table 3 are composed of those grains which have more than one obliquity and have diffraction patterns, such as those of specimens 255 and 93 in Fig. 6, which contain additional peaks indicating the presence of potassium feldspar with zero or low obliquity (this is also true of severa potassium feldspars, examined in a porphyroi from the Mirarrmina Complex, Arnhem Land, which are included here in view of their textural similarity to those of the Warrego

DIFFRACTOMETER TRACES OF SINGLE MEGACRYSTS FROM THE WARREGO PORPHYROID



Or - ORTHOCLASE   Mi - MICROCLINE   Ab - ALBITE

POTASSIUM FELDSPAR MEGACRYSTS

Porphyroid).

With regard to their maximum obliquities, the megacrysts of this group are more variable than those of Group 1, and all but two values fall within the range 0.61 - 0.78. Microcline having obliquity values such as these are considered by Tilling (1968) to be of intermediate structural state.

This grouping of the megacrysts of the Warrego Porphyroid on the basis of X-ray powder patterns is not reflected in the values of their optic angles which have almost identical averages in each group.

Variation within hand specimen.

Up to this stage, only single or in a few cases, several potassium feldspar megacrysts have been measured from each han specimen (Table 3). The question arises, especially in view of the work of Smithsom (1963), as to how representative (in terms of obliquity) of the megacryst population in the individ hand specimens are one or two grains.

Accordingly, ten megacrysts were measured from each of two hand specimens of the Warrego Porphyroid, one specimen fro each of Groups 1 and 3.

The measurements are listed in Table X (Appendix II), and illustrate that although the range of obliquities in each of the two rock specimens is greater than the precision of the method ($\pm$0.02), it is consistently less than 0.10, suggesting that :-

a) on the scale of a hand specimen, the megacrysts are reasonably homogeneous with respect to obliquity, and hence

b) one or two megacrysts are likely to represent in obliquity all the grains in a hand specimen.

2) Composition of megacryst individuals.

Compositional data was obtained on individual potassium feldspar megacrysts (24 from the Warrego Porphyroid and 12 fro the Black Eye Porphyroid) by accurately recording the position of the $\bar{2}01$ X-ray peak using potassium bromate as an internal standard according to the X-ray powder diffraction method (Appendix II), of Orville (1967). The feldspar powders were X-rayed prior to heating and then an attempt was made at dry homogenisation by heating them in air at a temperature of 1040°C (i.e. near the solidus) for 24 hours. In both cases, the resulting parameters were referred to Orville's curve for triclinic feldspars as heating merely produced marginal reductions in the obliquities of the potassium feldspars (Table X, Appendix II).

Perthitic relationships.

The potassium feldspar is microperthitic, the plagioclase being present as regular or irregular patches, 0.2 mms. in siz down to the limit of microscopic resolution and is of variable development both among and within grains.

Individual grains in the Warrego Porphyroid show increase in the volume of intergrown plagioclase which, in some cases, reaches up to 50% of the grains occurring in related patches and veins and commonly possesses chess-board twin patterns. These are clearly of replacement origin. Megacrysts, bearing plagioclase in this textural relationship, were omitted from the grains listed in Table 3.

The average, approximate content of plagioclase in perthi relationship estimated from the increase of plagioclase in sol solution in the megacrysts (in Table 3 and Fig. 5) on heating, are 12 and 15 mol. % for the Warrego and Black Eye Porphyroids respectively.

The Warrego potassium feldspars show the greatest variati

a) Composition of the potassic phase.

The compositions of potassic phases (representing 80 to 90% by volume of the megacrysts) are listed in Table 3 and plotted on Fig. 5.

The amount of plagioclase in solid solution within the potassium-rich phase varies up to a maximum of 6 wt %, which i similar to the range found in microclines examined by Goldsmit and Laves (1961) and Hall (1966a).

Of the zero values which occur, most belong to these megacrysts in the Warrego Porphyroid which have variable obliquities (i.e. including small or zero obliquities). These zero compositional values suggest that it may be more appropri to refer the $\bar{2}01$ peak position of the Group 3 feldspars to the sanidine (zero obliquity) curve of Orville, in which case the amount of plagioclase in solid solution ranges from 2 to 5½ wt %.

It is interesting to note that Goldsmith and Laves (1961) recorded negative values for plagioclase in solid solution in microclines even after correction for obliquity (their method of investigating composition involved the position of X-ray peak 400).

Both Goldsmith and Laves (1961) and Wright (1964) found that orthoclases studies by them contained more albite in solid solution than do microclines. In contrast, Hall (1966a) discovered that monoclinic or low-obliquity potassium feldspar from the Ardara pluton were no more sodic in composition than microcline microperthites from the same area. In agreement with the latter case, the Group 3 feldspars of the Warrego Porphyroid, regardless of which of Orville's curves is consult have no more sodic compositions than their associated, maximum microclines.

b) Bulk composition.

After being heated continuously in a furnace for 24 hours at a temperature of 1,040°C, most of the grains showed increas contents of albite in solid solution (estimated by the $\bar{2}01$ peak position) as recorded in Fig. 5 and Table 3.

Variations in bulk composition of megacrysts (i.e. those variations greater than the precision of the method which is $\pm$ 1 mo % Ab + An) occur both among and within samples from the same occurrence. This is particularly true of the Warrego Porphyrc (Fig. 5, Table 3). On the average, the potassium feldspars of Warrego and Black Eye Porphyroids increased their content of albite in solid solution to around 15 mol. % of Ab and An (Table 3).

No further heating tests were conducted to discover wheth complete homogenization was achieved in the 24 hours heating time. Parsons (1968) has indicated that some perthites requir periods of heating considerably in excess of 24 hours and that some apparently do not homogenize at all.

However, the following are consistent with an approach to homogenization :-

a) in qualitative terms, the increase in plagioclase in solid solution in the lattice of any particular potassium feldspar grain, appears in direct proportion to the amoun of plagioclase microscopically visible in that feldspar megacryst,

and,

b) the average bulk composition of all grains measured b the X-ray ($\bar{2}01$) diffraction method from the Warrego and the Black Eye Porphyroid respectively, agrees fairly well (Table XI, Appendix II) with the average composition of corresponding feldspar separates analysed by X-ray fluorescence methods.

Composition of megacryst separates.

In conjunction with the X-ray diffraction study, which has supplied limited compositional information on individual feldspar megacrysts from a relatively large number of rocks, 26 in all as presented in Table 3, more comprehensive analysis was undertaken using X-ray fluorescence and flame photometer methods (Appendices VI and VII) and involved both major and trace element determinations on 9 feldspar separates divided between porphyroidal occurrences in the following manner :-

Warrego	. . .	6 samples
Black Eye	. . .	3 samples

The majority of the feldspar separates selected are from rocks which were analysed in the course of this investigation.

As mentioned in the textural section, the potassium feldspars of the porphyroids contain a considerable quantity of inclusions, such as quartz, biotite and chlorite. After hand picking and crushing, the feldspar separates were sieved and purified using heavy liquids and a Cook isodynamic magnetic separator. These processes are expected to yield grain separates which will be fairly representative of the bulk composition of the K-feldspars, i.e. the separates will not be noticeably depleted in plagioclase present in perthitic relationship (Appendix V).

Analyses of the potassium feldspars are presented in Tabl 4 along with their structural formulae.

The tendency for the ionic values to be slightly low in the X-group of the structural formula of some of the analyses probably indicates that not all the impurities (particularly quartz) have been successfully removed during treatment. In connection with this, the Fe_2O_3 content in a number of cases is over the 0.5% value which is, according to Deer, Howie and Zussman (1963), about the maximum limit for substitution of Fe^{3+} in the normal feldspar lattice. This excess probably represents ferromagnesian impurities.

Major and selected trace constituents.

In mol. % albite, the Black Eye potassium feldspars have values of 12.9 to 15.5% which are included by the wider variation of 11.9 to 23.7% for the Warrego samples.

The mol. % anorthite shows little variation among samples all values falling within the range 0.5 to 1.2%.

In content of rubidium and barium, the Warrego potassium feldspars have ranges of 279 to 439 p.p.m. and 2262 to 4006 p.p.m. respectively, which embrace the corresponding values of 383 to 427 p.p.m. and 2504 to 2590 p.p.m. for the Black Eye samples.

Table 4.

Major element and selected trace element compositions in potassium feldspars in porphyroidal and granitic rocks at Tennant Creek.

POTASSIUM FELDSPARS IN PORPHYROIDAL AND GRANITIC ROCKS

	Warrego						Black Eye			Creek Bed	Station Hill Granite				Enclaves	
Specimen	2	5	51	61	62	401	479	480	477	606■	G	510/11	632	621	518	519
SiO_2	65.67	64.24	64.68	65.60	66.08	64.86	63.83	63.44	64.46	68.55	65.73	64.16	64.92	65.24	64.41	64.53
Al_2O_3	18.19	18.80	19.60	19.49	19.23	18.34	18.70	19.40	18.94	19.55	19.06	18.84	18.79	18.02	19.07	18.58
Fe_2O_3	0.49	0.59	0.42	0.35	0.37	0.38	0.64	0.49	0.71	0.34	0.37	0.37	0.37	0.37	0.51	0.84
CaO	0.14	0.18	0.13	0.14	0.18	0.10	0.24	0.10	0.11	0.25	0.25	0.22	0.28	0.19	0.28	0.65
Na_2O	1.27	2.02	2.68	2.43	1.64	1.30	1.55	1.44	1.63	10.10	2.26	2.30	2.35	2.02	1.74	2.19
K_2O	14.05	13.57	12.90	12.23	13.47	13.93	13.70	14.53	13.32	0.59	12.78	13.46	13.07	13.48	13.59	12.04
P_2O_5	0.08	0.05	0.02	0.03	0.07	0.03	0.08	0.04	0.07	0.06	0.07	0.07	0.08	0.06	0.05	0.05
Rb_2O	0.04	0.03	0.04	0.04	0.03	0.05	0.04	0.05	0.04	0.00	0.06	0.06	0.04	0.05	0.04	0.03
SrO	0.02	0.02	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01
BaO	0.42	0.35	0.25	0.28	0.45	0.35	0.29	0.29	0.28	0.02	0.31	0.33	0.39	0.45	0.46	0.41
Total	100.37	99.85	100.73	100.60	101.54	99.35	99.08	99.79	99.57	99.47	100.90	99.82	100.31	99.89	100.16	99.33
Structural formulae on the basis of 32 oxygens																
Si	12.039	11.858	11.790	11.894	11.939	11.998	11.873	11.763	11.894	12.025	11.933	11.850	11.902	12.023	11.823	11.900
Al	3.931	4.091	4.210	4.162	4.096	4.001	4.101	4.241	4.117	4.043	4.079	4.101	4.058	3.915	4.125	4.036
Fe^{3+}	0.067	0.081	0.057	0.047	0.051	0.053	0.091	0.068	0.100	0.045	0.051	0.052	0.052	0.052	0.052	0.117
Ca	0.028	0.035	0.024	0.027	0.035	0.019	0.047	0.019	0.022	0.047	0.049	0.044	0.055	0.039	0.055	0.127
Na	0.451	0.723	0.948	0.853	0.576	0.465	0.559	0.518	0.583	3.434	0.797	0.826	0.834	0.722	0.619	0.781
K	3.285	3.194	3.000	2.828	3.104	3.287	3.250	3.436	3.136	0.132	2.960	3.171	3.057	3.169	3.182	2.831
Rb	0.006	0.004	0.005	0.005	0.004	0.007	0.006	0.007	0.006	0.000	0.007	0.007	0.006	0.007	0.006	0.004
Sr	0.002	0.002	0.001	0.001	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.001	0.001	0.001
Ba	0.031	0.026	0.018	0.020	0.031	0.026	0.021	0.021	0.020	0.001	0.022	0.024	0.028	0.032	0.033	0.030
Z group	16.037	16.030	16.057	16.103	16.086	16.052	16.065	16.072	16.111	16.113	16.063	16.003	16.012	15.990	16.000	16.053
X group	3.803	3.984	3.996	3.734	3.752	3.805	3.884	4.002	3.768	3.615	3.836	4.073	3.982	3.970	3.896	3.774
Mol. % feldspar components (Ba, Rb and ½ Sr included in Or)																
Or	87.4	80.9	75.7	76.4	83.7	87.3	84.4	86.6	83.9	3.7	77.9	78.6	77.6	80.8	82.7	75.9
Ab	11.9	18.1	23.7	22.8	15.4	12.2	14.4	12.9	15.5	95.0	20.8	20.3	20.9	18.2	15.9	20.7
An	0.7	0.9	0.6	0.7	1.0	0.5	1.2	0.5	0.6	1.3	1.3	1.1	1.4	0.9	1.4	3.4
Trace elements (ppm)																
Rb	336	301	332	330	279	439	407	427	383	16	560	521	348	457	344	307
Sr	210	135	120	114	143	108	83	79	85	36	69	79	133	116	96	104
Ba	3732	3093	2262	2485	4006	3181	2590	2584	2504	77	2743	2921	3466	4076	4116	3656
Δ	0.86	0.86	0-0.89	0.87	-	0.89	0.89	0.90	0.90	1.10†	0.92	0.93	0.90	0.91	0.91	0.85
$2V_x$°	74-76	71-76	68-73	69-76	-	78-80	74-82	68-83	67-83	95-107	76-89	76-85	79-87	81-85	79-84	82-87

The strontium values of 79 to 85 p.p.m. for the Black Eye feldspars are lower than the range of 108 to 210 p.p.m. for the Warrego samples.

2. PLAGIOCLASE.

Texture.

The plagioclase feldspar megacrysts commonly range up to mms. in size, although some reach 7 mms. They have a variety of pale colours such as red, yellow or white and are present a subhedral grains which, in some cases, approximate to rectangu shapes.

In thin section, the plagioclase has a dusty appearance due to a white micaceous alteration product. The grains are unzoned (see however, specimen 94) and twin laws identified on a universal stage by the method of Slemmons (1962a) are albite, carlsbad, albite-carlsbad and pericline. In some case the twin composition surfaces are irregular. According to the criteria proposed by Vance (1961), much of the lamellar twinni appears to be of secondary origin and related to deformation.

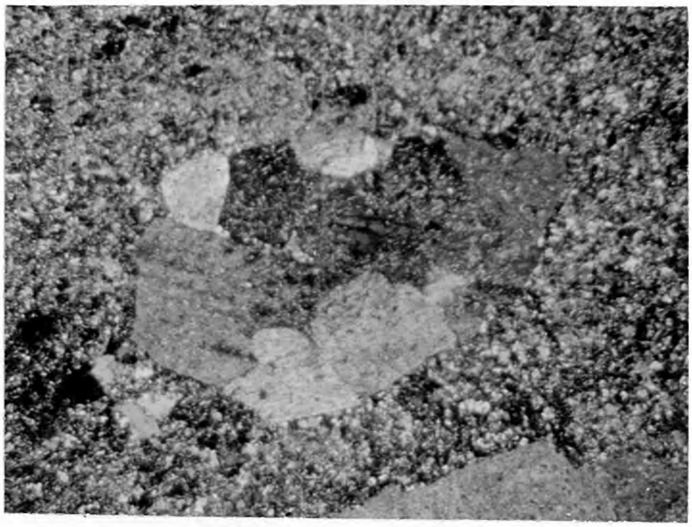
Many of the grains are composed of various sub-individual with mutually interlocking boundaries (Plate 10a and b). The enveloping surface of such associations tends to be composed o regular crystal faces and, where the perimeters of the sub-individuals meet, re-entrant angles are common.

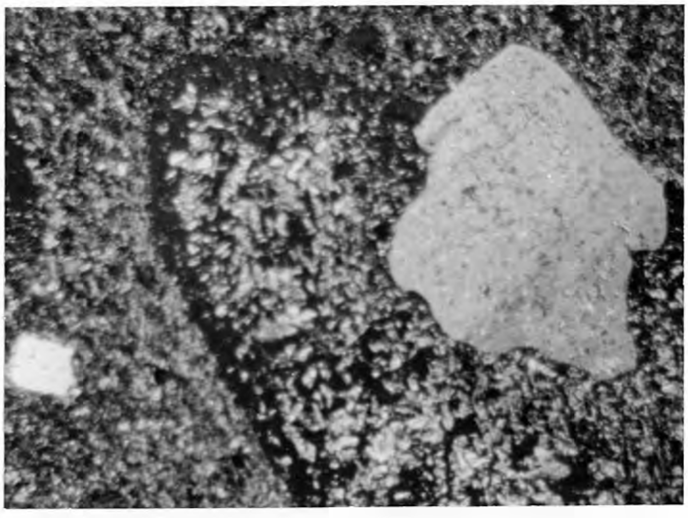
These relationships suggest that the composite plagioclas grains have formed by coalescence of individuals rather than b

Plate 10 (a) - Warrego Porphyroid (width of field - 3 mms; crossed polars).

Composite plagioclase megacrysts - possibly due to synneusis - in the porphyroids.

Plate 10 (b) - Black Eye Porphyroid (as above).





the recrystallization of original single grains.

As a rule, the plagioclase has few inclusions and does no possess embayments or cavities.

The occurrence of plagioclase in specimen 94 demands special mention. In addition to being present in grains of typical habit, some of which contain traces of oscillatory zoning, the plagioclase also entirely composes the larger grains which are normally formed of potassium feldspar in the full, most common, megacryst assemblage (Table I (a)). In thi association, plagioclase is considered to have replaced the potassium feldspar megacrysts with preservation of simple twin patterns and embayment and cavity textures (Plate 5c).

<u>Optical determination</u>.

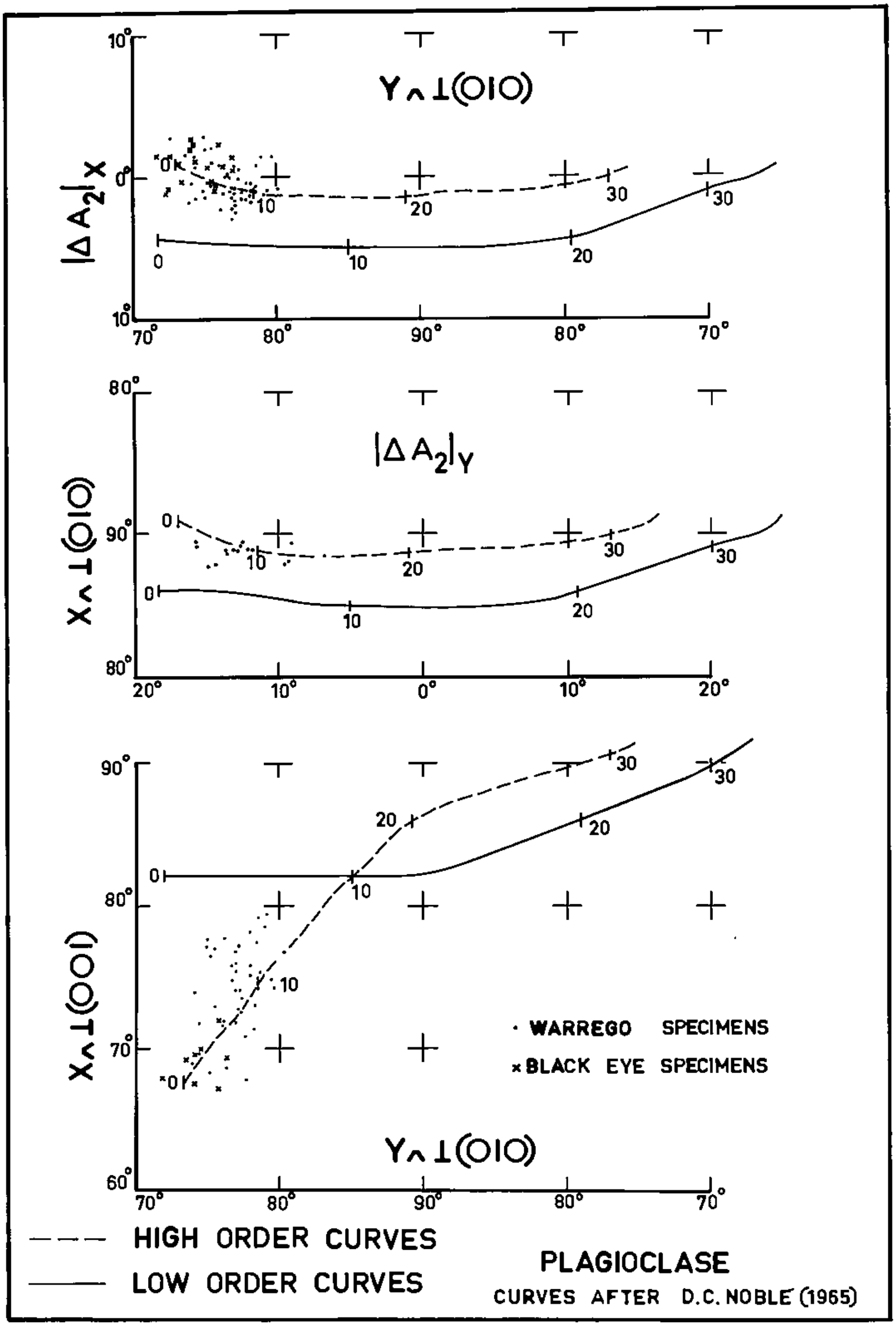
1) Orientation of the optical indicatrix.

Information on the orientation of the optical indicatrix in the plagioclase grains was obtained by employing a 5 - axes universal stage technique outlined by Noble (1965a)and discuss in Appendix III.

The measured parameters are presented in Fig. 7 in which they are plotted on charts of Noble (1965a)derived from data o other workers (see Appendix III). The plagioclase from both t Warrego and Black Eye Porphyroids prove to be mainly albite in composition and to relate to the high-order, structural state curves.

Figure 7.

Order-disorder relationships in plagioclases of the porphyroidal rocks as determined by optical measurements - the orientation of the optical indicatrix.



PLAGIOCLASE

CURVES AFTER D.C. NOBLE (1965)

2) Optic axial angle.

In the course of the above manipulations with the univers stage, the optic axial angles of the plagioclase megacrysts we measured using the orthoscopic extinction method.

The optic axial angle, 2Vx, of most of the plagioclase is within the range 90 to 100^{o} (Tables 5 and 6). When 2Vx is considered along with composition on the diagram of J.R. Smith (1958), presented in Fig. 8, the plagioclases are seen to occur on the high-order curve as they do in the first optical method

The plagioclase present in other textural relationships, such as :

a) the pseudomorphs after potassium feldspar,

b) euhedral inclusions within the potassium feldspar grains,

and

c) rare rims around potassium feldspar grains,

is also related to the high-order curves with respect to optic orientation and optic axial angle.

3) Refractive indices.

Refractive index measurements were checked (Appendix III) on the plagioclase from several specimens of the Warrego Porphyroid and found to be typical of the albite composition (Table 6).

<u>X-ray determination</u>.

X-ray diffraction measurements were obtained from powdere

TABLE 5.

Optical and X-ray data on plagioclase from the Warrego Porphyroid.

specimen	$2Vx^{o}$	X-ray peak separation $131 - 1\bar{3}1$	$\bar{1}32 - 131$	Composition by optics		
281	97	1.12	2.65	An_{9}^{+}	M	
285	92-102	-	-	An_{9}	M	
277	94-100	1.23	2.60	An_{8}	M	
275*	-	1.22	2.66	An_{9}^{+}	M	
271	-	1.22	2.65	An_{9}^{+}	M	
1	-	1.28	2.65	An_{6}	M	
216	99	-	-	An_{4}	M	
94	94	-	-	An_{5}	M	An
58	98-99	1.12	2.70	An_{6}	M	
80	93-95	-	2.60	An_{8}	M	
401	97-98	-	2.67	An_{9}	M	An
94(a,b)	97-98	-	-	An_{41-38}	M	
94(a)	98	-	-	An_{45}	I in L	
94(a)	84	1.48	-	$\simeq An_{20}$	LM	
94(b)	82	1.53	-	$\simeq An_{20}$	LM	
401	-	-	-	$An_{9,4}$	I in L	
401	-	-	-	An_{15}	R	

* precision $\pm$ 0.03 $\pm$ 0.01 in degrees 2θ

+ refractive index measurements

† normative value

M - megacryst , I in LM - inclusion in large magacryst, LM - large megacryst, R - rim of large megacryst.

TABLE 6.

Optical and X-ray data on plagioclase from the Black Eye Porphyroid.

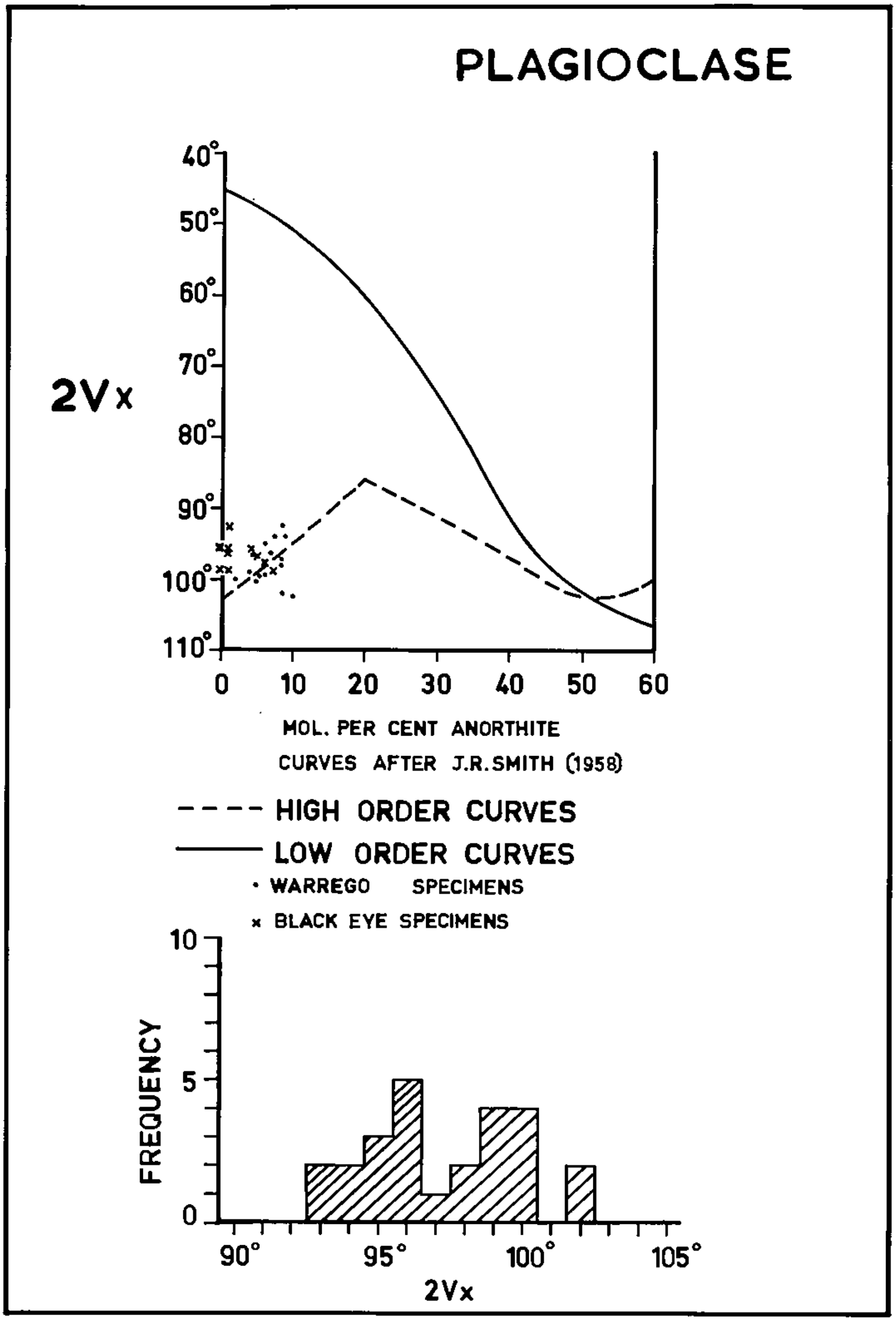
Specimen	$2Vx^{\circ}$	X-ray peak separation $131 - 1\bar{3}1$	$\bar{1}32 - 131$	Composition by optics	
481	96-99	-	-	An_2	M
483	93-99	-	-	An_4	M
491	99-100	1.14	2.72	An_2	M
479	98-104	1.19	2.79	An_4	M
480	-	-	-	$An_{2,4}$	R

Refractive indices of plagioclase from the Warrego Porphyroid.

281	N_{glass}	1.4957 ± 0.0007
271	Ny	1.537 ± 0.001
275	Ny	1.537 ± 0.001

Figure 8.

Order-disorder relationships in plagioclases of the porphyroidal rocks as determined by optical measurements - the optic axial angle.


PLAGIOCLASE
2Vx
40°
50°
60°
70°
80°
90°
100°
110°
0
10
20
30
40
50
60
MOL. PER CENT ANORTHITE
CURVES AFTER J.R.SMITH (1958)
HIGH ORDER CURVES
LOW ORDER CURVES
• WARREGO SPECIMENS
× BLACK EYE SPECIMENS
10
5
0
FREQUENCY
90°
95°
100°
105°
2Vx

plagioclase separates hand picked from specimens of the Warreg
and Black Eye Porphyroids. The separationsof selected peaks (Appendix III) were recorded, listed in Tables 5 and 6 and plotted in Fig. 9 along with the average composition of the plagioclase in each specimen as determined optically.

The plots lie on or near the high-order curves, which is complete agreement with the optical results.

Although the plagioclases are in the composition range in which peristerites occur (i.e. albite to oligoclase), no unmixing has been recognized in their X-ray diffraction patter

Composition.

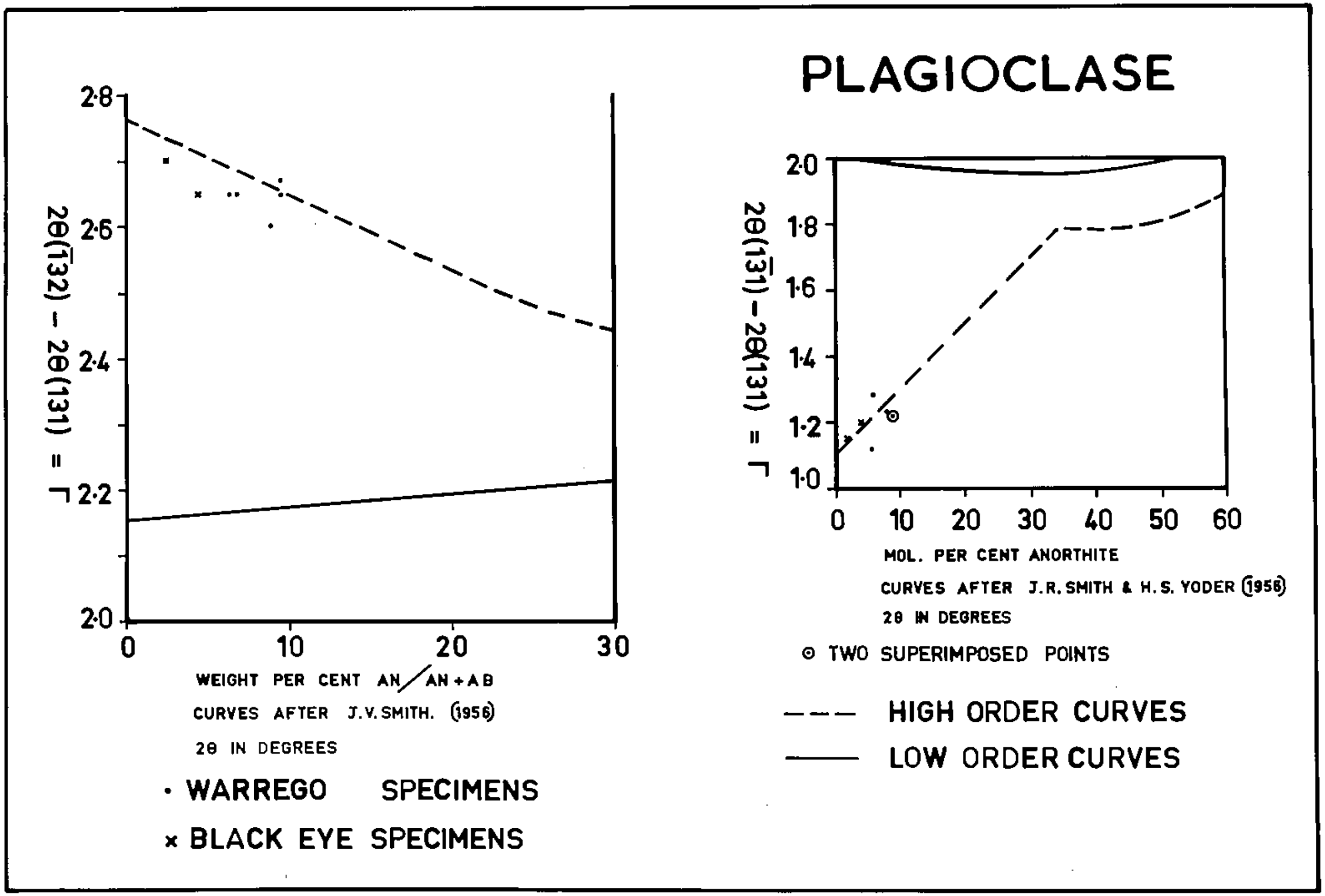
The composition of individual plagioclase megacrysts determined optically as already described, ranges from An0 to An15 (Fig. 7). These are averaged for individual rock specime and listed in Tables 5 and 6 where the range is An2 to An9.

The grains in specimen 94, having typical plagioclase habits but with traces of oscillatory zoning, are found to be of andesine composition. The larger grains considered to be plagioclase pseudomorphs after potassium feldspar have an oligoclase composition. Occasional euhedral plagioclase inclusions in these large pseudomorphs are of andesine.

The occasional plagioclase inclusions recorded in unalter potassium feldspar megacrysts are albite, while the rare rims plagioclase around the potassium feldspar are either albite or oligoclase.

Figure 9.

Order-disorder relationships in plagioclases of the porphyroidal rocks as determined by X-ray diffraction methods.



PLAGIOCLASE
2θ(1̄32) – 2θ(131) = Γ
2·8
2·6
2·4
2·2
2·0
0
10
20
30
WEIGHT PER CENT AN/AN+AB
CURVES AFTER J.V. SMITH. (1956)
2θ IN DEGREES
· WARREGO SPECIMENS
× BLACK EYE SPECIMENS
2θ(13̄1) – 2θ(131) = Γ
2·0
1·8
1·6
1·4
1·2
1·0
0
10
20
30
40
50
60
MOL. PER CENT ANORTHITE
CURVES AFTER J.R. SMITH & H.S. YODER (1956)
2θ IN DEGREES
⊙ TWO SUPERIMPOSED POINTS
HIGH ORDER CURVES
LOW ORDER CURVES

The plagioclase megacrysts were not analysed for major elements. The barium and strontium contents of a limited numb of samples hand-picked from the Warrego and Black Eye Porphyro (three and two samples respectively), were measured by emissio spectrography (Appendix IX) and the values listed in Tables 7 and 8.

The barium contents of the two Black Eye samples are lowe at 240 and 260 p.p.m. than those of the Warrego specimens whic range from 330 to 480 p.p.m. The strontium contents of all samples are generally similar, ranging from 70 to 110 p.p.m.

3. QUARTZ.

Average dimensions for the pale blue to glassy quartz grains are in the range 6 to 10 mms. In the main, these mega-crysts show no regular crystal faces and boundaries of the grains are sinuous being characterized by embayments. In cross-section, the grains often present roughly elliptical outlines (Plate 11a), while others have a tendency to be squar or rhombic. The embayments projecting into the grains are responsible for the zoned and spotted appearance of many of th quartz crystals in hand specimen.

The embayments tend to be in the form of lobes with smoot curving edges (Plate 11b) producing gentle cuspate-shaped outlines normally convex towards the embayments. Internal cavities are also present, showing the same characteristics an

TABLE 7.

Ba (ppm) in coexisting feldspars in porphyroids and granites.

	potassium feldspar	plagioclase
Warrego Porphyroid		
Specimen 58	2100	330
" 80	3100	480
" 401	3181	400
Black Eye Porphyroid		
Specimen 479	2590	260
" 491	2600	240
Creek Bed Porphyroid		
Specimen 606	77*	150
Granite		
Specimen 632	3466	280
" 510/11	2921	230
" G	2743	370
" 621	4076	320

* potassium feldspar replaced by plagioclase.

TABLE 8.

Sr (ppm) in coexisting feldspars in porphyroids and granites.

	potassium feldspar	plagioclase
Warrego Porphyroid		
Specimen 58	70	90
" 80	120	110
" 401	108	100
Black Eye Porphyroid		
Specimen 479	83	100
" 491	60	70
Creek Bed Porphyroid		
Specimen 606	36*	20
Granite		
Specimen 632	133	190
" 510/11	79	170
" G	69	160
" 621	116	150

* potassium feldspar replaced by plagioclase.

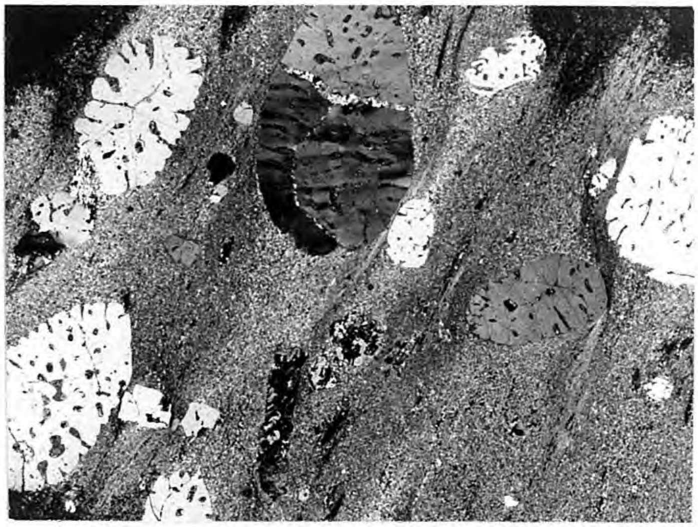
Plate 11 (a).

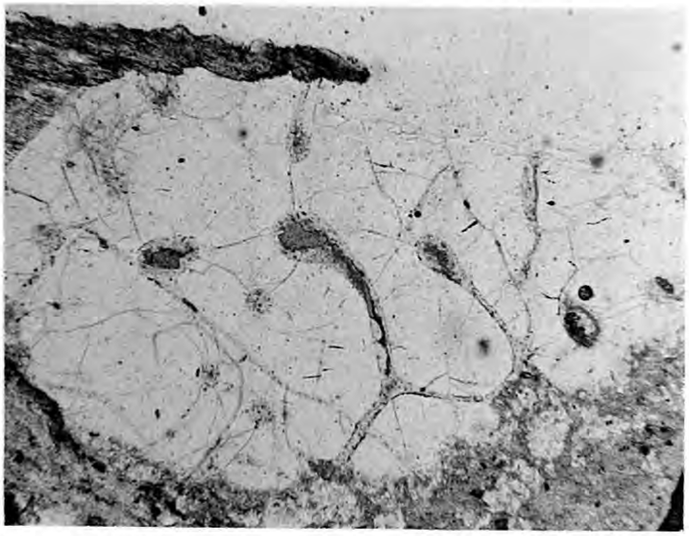
(X4; crossed polars)

Quartz megacrysts with embayments and cavities in the Warrego Porphyroid.

Plate 11 (b).

(X30; crossed polars)





also having circular, elliptical, triangular and square sectio

There is apparently little structural control of the embayments and internal cavities by the quartz lattice, as no preferred orientations are evident other than a radial distribution of the embayments projecting into the grains. Due t the transparency of the quartz, it is possible to see in hand specimen that the internal cavities are connected to embayment and hence to the exteriors of the crystal grains.

The embayments and cavities contain the same material as the potassium feldspar; no distinctive textures were recorded.

In some cases, the quartz grains are composed of a number of sub-individuals, slightly disorientated optically with respect to one another and bounded by fractures which may cont small polygonal grains of recrystallized quartz. Embayments c be seen crossing several sub-individuals, thereby suggesting that the quartz mosaics result from the recrystallization of a single, embayed individual.

4. BIOTITE.

Biotite, (X - straw yellow; Y, Z - greenish brown) tend to form mainly irregular clusters and nests up to a few millimeters across, some of which show regular outlines in part possibly indicating the former presence of another ferromagnesi mineral. The biotite is partly altered to chlorite.

Contact relations.

The bottom contacts of the quartz-feldspar porphyroid wit the underlying rocks are irregular in detail on the core specimen scale. The grain-size of the porphyroid is maintaine right up to the contact where megacrysts from that rock are pressed into the adjacent rocks, causing indentations with reciprocal minor 'flames', a few millimeter long, of the count rock to reach into the coarser porphyroid (Plate 12). These features appear similar in nature to load structures described in unconsolidated sediments (Dzulynski and Walton, 1965). Locally, the porphyroid interfingers with the contact rocks isolating wisps of the latter within itself and, in places, sends thin, branching apophyses into the country rock to a distance of at least 5 cms. (Plate 12 a).

No information is available at this locality on the main upper contact of the presumed porphyroidal horizon, as it has not been investigated by drilling. Intersections of rocks similar to the fine-grained country rocks are encountered in t of the drill holes, D.D.H. 13 and 15 (Fig. 4), above quartz-feldspar porphyroid. The significance of these are not appare at this stage. They may represent bands or lenses within the porphyroid or alternatively could be salients of country rock projecting into the porphyroid from the main contacts.

The only contact of the quartz-feldspar porphyroid with these rocks, preserved in any detail, is the upper contact of

Plate 12 (a).

(width of field - 5 inches)

Contact features of the Warrego Porphyroid and country rocks as recorded in core specimen.

Plate 12 (b).

(width of field - 7 inches)

the bottom band of quartz-feldspar porphyroid in D.D.H. 15. It has the following section :-

	country rock	
		sharp
6'	porphyroid	
		gradational
5'	porphyroid intermixed with country rock	
		gradational
8'	country rock	
		sharp
	porphyroid	

Hence, a zone of banding marks the passage of quartz-feldspar porphyroid to fine-grained country rock similar to th bottom contact in D.D.H. 2 (Fig. 4). Some intermixing of the rocks is also apparent here.

No erosional characteristics are apparent at either the lower or upper contacts of the quartz-feldspar porphyroid and there is no clear evidence of hornfelsing, although within 2 m of the contact in D.D.H. 5, the fragmental pattern of an ash becomes less distinct as the minerals form a fine granoblastic aggregate (specimen 95).

In summary, irregular contacts with intermixing and interbanding features are characteristic of the quartz-feldspa porphyroid in this area.

Associated rocks.

The rocks found in contact with, or in close association with, the quartz-feldspar porphyroid are described in turn.

1) The Phyllitic Rocks.

Below the quartz-feldspar porphyroidal body, the drill holes encounter up to 1,000 feet of phyllitic rocks containing bands of quartz porphyroid ranging in thickness from a few inches up to 250 feet (Fig. 4).

The phyllites, grey to green in colour, are present as a series of medium-to fine-grained rocks in which stratification is scarce, being confined to some graded bedding in the coarser rocks and occasional faint laminations in the finer rocks (e.g specimen 247). As viewed in the core specimens, the contacts of the medium-and fine-grained rocks are characteristically irregular, a feature which appears to pre-date the schistosity as there is no significant transposition of contacts along schistosity surfaces, which might account for it.

Green porphyroblasts of chlorite, found only in some of the fine-grained rocks, may reach up to 4 mms. in size (e.g. specimen 247) and have a generally ovoid shape with a curious annular appearance, as the material is concentrated on the margins and sometimes in the centre.

Petrographic Features.

The mineral assemblage consists of variable amounts of quartz, muscovite and chlorite with such accessories as tourma line, apatite, zircon and opaque minerals. Numerous rock fragments up to 1 mm. in size, mainly chert, are orientated in the schistosity in the coarser varieties (specimen 309). Biotite (X-straw yellow; Y, Z -green-brown) occurs rarely as complete grains, but more often as traces within the chlorite cleavages.

The chlorite shows pleochroism from light yellow to blue-green, has traces of pleochroic haloes and exhibits anomalousl low birefringence colours in green, brown and purple. It can length fast or slow in optical elongation. The occurrence of biotite as traces within the chlorite cleavages and the dusty appearance of some of the grains due to fine sphene granules, suggests that at least some of the chlorite has formed from biotite.

All the rocks have a fabric composed of a mineral alignment of muscovite and chlorite forming a schistosity which is best developed in the fine-grained varieties where the quartz grains also contribute.

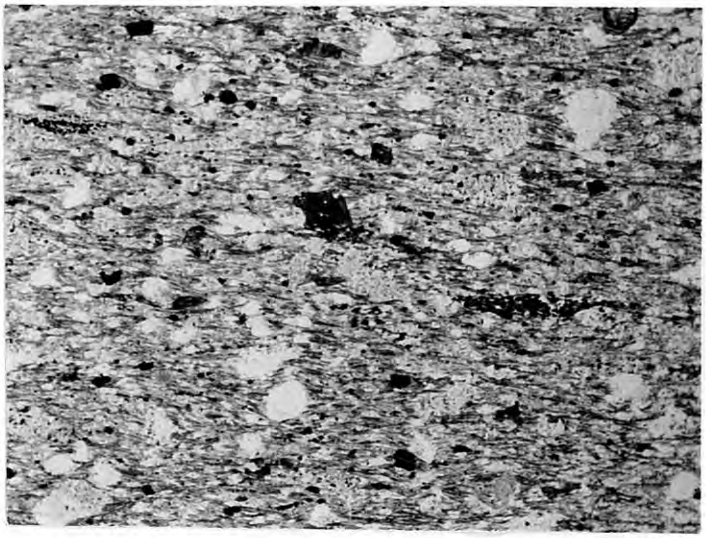
In the coarser types (e.g. specimens 246 and 309), angula to sub-angular quartz grains, some recrystallized, reaching 0. mms. in size, and variable amounts of rock fragments, possibly chert, up to 1 mm. long and elongate in the schistosity, are wound around by a finely textured, foliated background consist of aligned white mica sheaves, quartz grains (0.06 mms.) and some chlorite (Plate 13a). Only a few minor chlorite

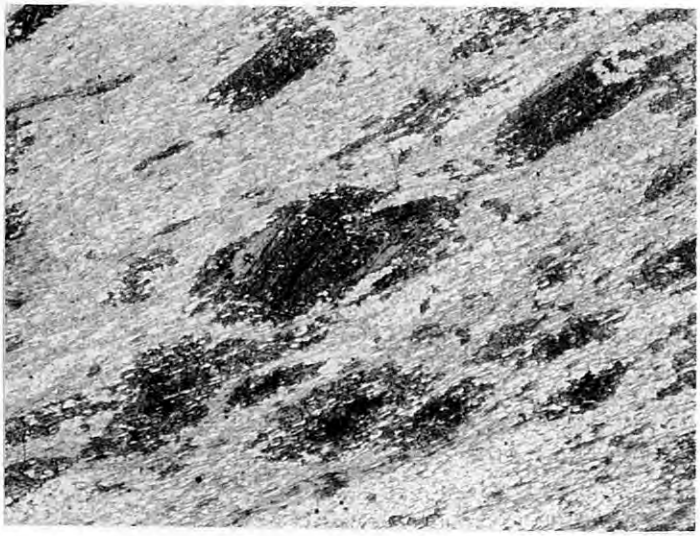
Plate 13 (a) - metamorphosed volcanic grey-wacke (X20; ordinary light).

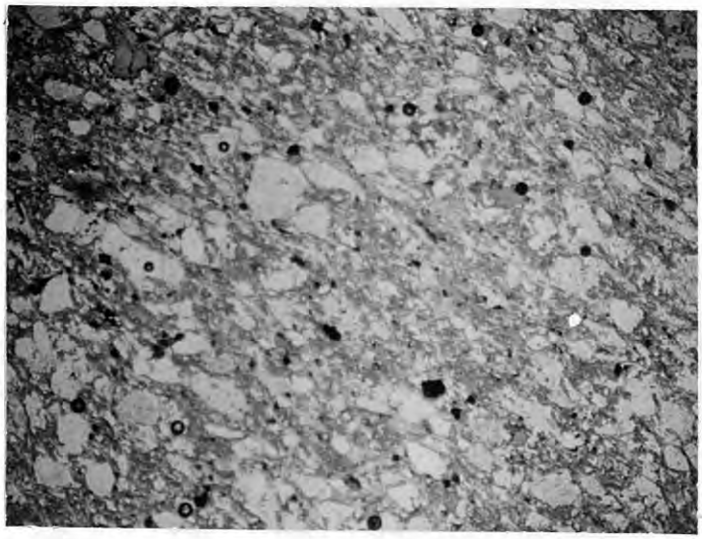
Metamorphosed wall rocks of the Warrego Porphyroid - thin sections.

Plate 13 (b) - metamorphosed volcanic ash. (as above)

Plate 13 (c) - metamorphosed volcanic greywacke. (width of field - 3 mms; ordinary light)







porphyroblasts occur.

The finer varieties (e.g. specimens 105, 116 and 247) hav an oriented fabric made up of elongate laths and aggregates of muscovite and some chlorite along with elongate quartz grains (0.1 mm.). Inclusion-rich chlorite porphyroblasts (Plate 13b) vary from small, well-shaped laths up to large, diffuse ovoids The quartz fabric can be traced uninterruptedly through the chlorite porphyroblasts which have formed subsequent to it. Af the growth of the porphyroblasts, deformation produced microfo in the schistosity and kink bands in the porphyroblasts.

When viewed in subdued illumination without crossed polar the fabric of the fine-grained rocks is shown to be vitroclast having a finely textured, fragmental character in which the distribution of quartz, white mica and chlorite outlines intricate spiculate shapes (typical of volcanic shards), which are still preserved in spite of being streaked out in the schistosity surface.

This is also true of the matrix of the coarser phyllites.

Classification.

In the light of the above descriptions, the relatively coarse phyllites, in which angular quartz grains and rock fragments are found, are considered to be tuffaceous greywacke and the finer phyllites to be volcanic ash deposits or vitric tuffs.

2) The Quartz Porphyroids.

These grey to green, variably foliated rocks have a spott appearance due to their content of embayed quartz megacrysts which is generally about 10 - 30% by volume, although this may vary erratically over small distances from the maximum value down to a few sparse megacrysts. The quartz grains are identical in detail to those described in the quartz-feldspar porphyroid and are set in a fine-to medium-grained, often foliated matrix of quartz, white mica and chlorite. The chlorite becomes abundant locally where, apart from the quartz megacrysts, the rocks may be regarded as monomineralic, chlorit schists.

Textures preserved in the groundmass mineralogy (Plate 14b are coarser representatives of the intricate patterns present in the quartz-feldspar porphyroid groundmasses and are interpreted as accumulations of shards of volcanic glass, since recrystallized.

The deduction that the groundmass of the quartz porphyroic rocks originally had a vitroclastic, non-welded nature suggests that these rocks are volcanic pyroclastics.

No bedding, banding or mineral stratification is present in these rocks. Only a few volcanic rock fragments occur as inclusions.

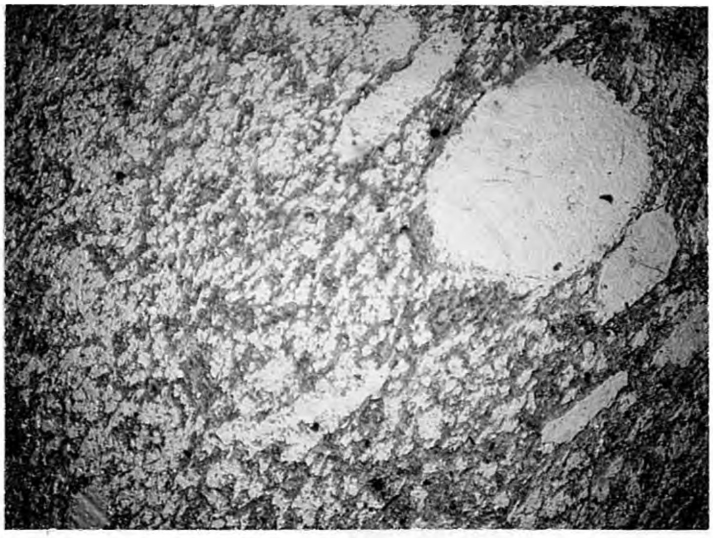
Mineralogical and chemical studies were not conducted on these rocks.

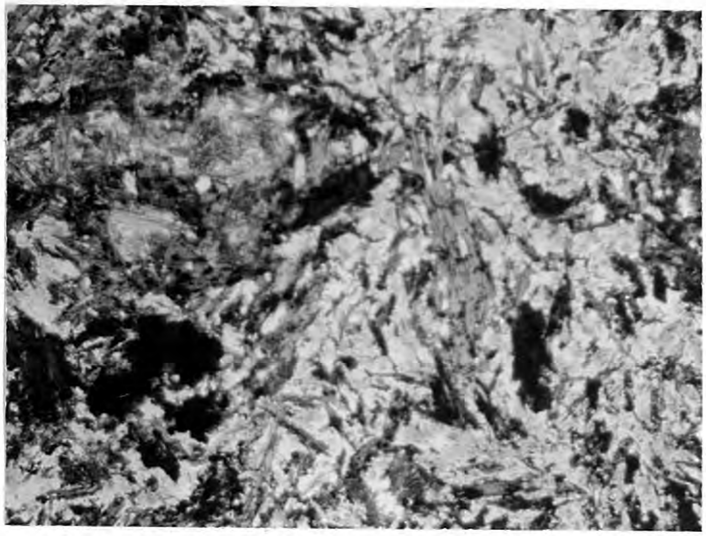
The quartz porphyroids gives way to the adjacent tuffaceou greywackes and ash deposits over wide zones in which the amou

Plate 14 (a) - heterogeneous quartz porphyroids in core specimen from the Warrego area.
(width of field - 6 inches)

Plate 14 (b) - thin section of quartz porphyroid showing vitroclastic groundmass from the Warrego area.
(width of field - 2 mms; ordinary light)

Plate 14 (c) - fabric of lamprophyre from the Warrego area (width of field - 3 mms; ordinary light).





of porphyroidal material in the shape of irregular patches of quartz porphyroid, or of separate quartz megacrysts, or irregular fragments of chloritic groundmass, gradually diminis These zones have a heterogeneous aspect (Plate 14a) due to the intermixing.

3) The Lamprophyres.

The rocks of this area are intruded by numerous bodies of lamprophyre ranging from a few feet to several tens of feet in thickness (Fig. 4). The lamprophyres are dark green to dark red, fine-to medium-grained rocks often with a spotted appearance due to leucocratic minerals contrasting with a dark background of biotite flakes. The rocks are sheared to varyin extents.

Petrographic Features.

The fabric of the relatively fresh rocks (e.g. specimen 63) is dominated by numerous thin, ragged biotite laths rangin in length from 2 mms. down to 0.1 mm. and having a decussate arrangement (Plate 14c). The biotite is accompanied in the groundmass by irregular actinolite and chlorite sitting in a granular mosaic of potassium feldspar grains which often clust to form sheaves or crude, partial rosettes about 0.5 mm. in diameter. Some quartz and minor apatite are found.

Leucocratic spots, observed in hand specimen, reach up to 2 mms. in size and prove to consist of nests of thin actinolit prisms surrounded by biotite aggregates and may represent uralitized pyroxene grains, although no relicts remain.

Biotite is pleochroic (X -light yellow; Y, Z -dark brown commonly deformed and gives way in places to chlorite along the cleavage planes. Minutes needles, probably of rutile, are enclosed in biotite and aligned in three directions 120° apart.

Potassium feldspar is untwinned, shows straight extinctio along the laths which are length fast in optical characte while the optic axial angle is negative and of moderate size.

The fresh lamprophyres can be classified as mica-lamprophyres or minettes.

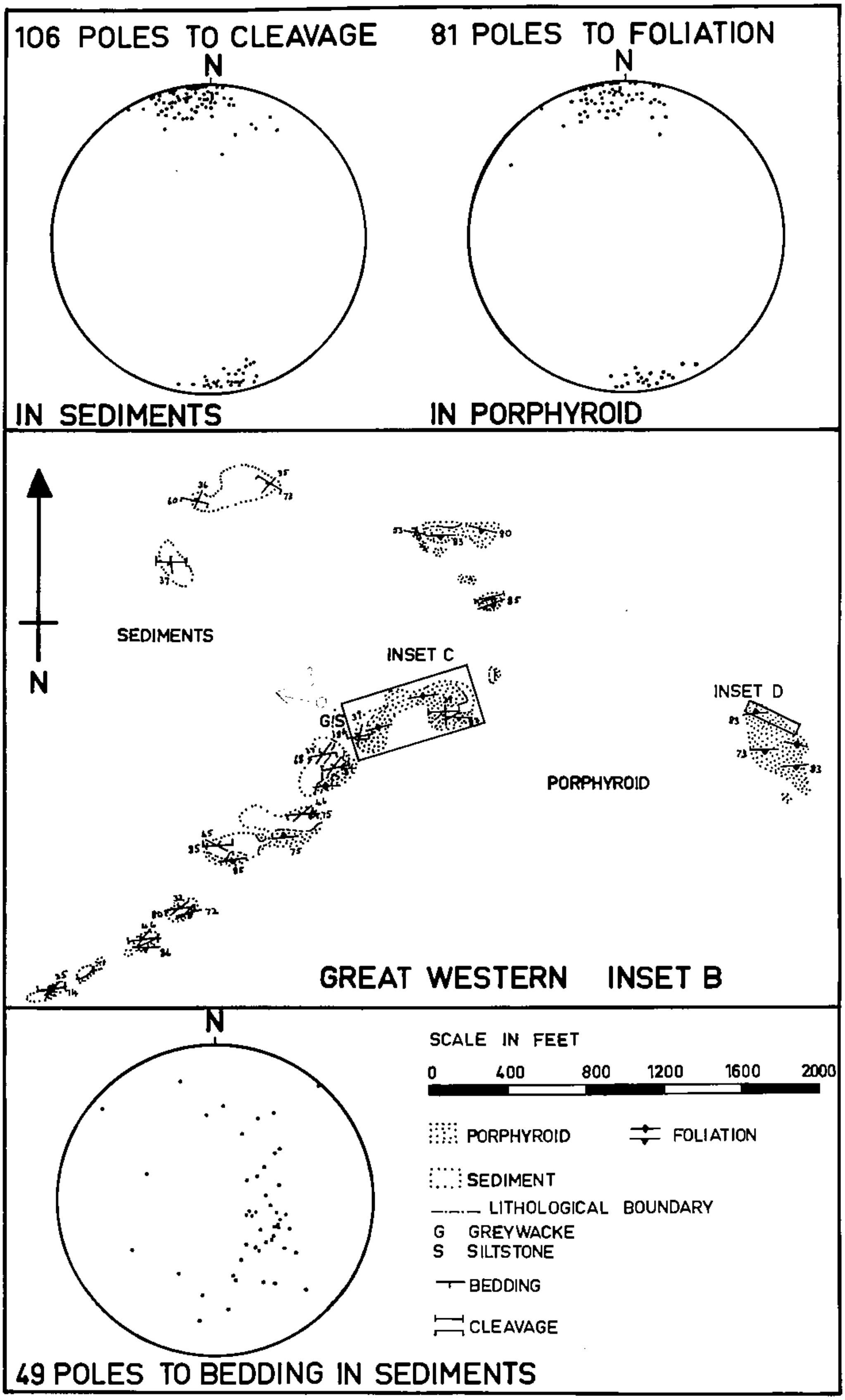
2. THE INSET B AREA.

In this area, the locality of which is shown in Fig. 2, the contact between quartz-feldspar porphyroid and the adjacen sediments is well enough exposed to make detailed mapping worthwhile.

The main outcrop pattern and distribution of porphyroid and sediment is reproduced in Fig. 10. The area was mapped using an enlarged aerial photograph (1 inch representing 400 feet). The top contact of the porphyroidal horizon is quite well exposed as it runs along a small line of low hills, while the bottom contact to the east is not visible, although the inset D area is thought to be close to it on very sparse outcr

Figure 10.

Geological sketch map and orientation of structures in the Inset B area.


106 POLES TO CLEAVAGE
N
IN SEDIMENTS
81 POLES TO FOLIATION
N
IN PORPHYROID
SEDIMENTS
INSET C
INSET D
G/S
PORPHYROID
N
GREAT WESTERN INSET B
N
SCALE IN FEET
0 400 800 1200 1600 2000
PORPHYROID
FOLIATION
SEDIMENT
LITHOLOGICAL BOUNDARY
G GREYWACKE
S SILTSTONE
BEDDING
CLEAVAGE
49 POLES TO BEDDING IN SEDIMENTS

evidence.

The Inset B Porphyroid.

The quartz-feldspar porphyroid is similar to that describ from the Warrego area except that no fresh material is availab from the area as no drilling has been attempted and the surfac rocks are extensively weathered.

The feldspars are wholly or partially replaced by finely-divided micaceous products, the exact nature of which has not been investigated. The fragmental textures in the porphyroida groundmasses are well-preserved (Plate 15a).

Small, irregular patches up to 4 mms. across occurring in some rocks (specimens 445 and 446) are composed almost exclusively of aggregates of stumpy laths of white to yellowis micaceous material with very low birefringence which may be kaolinite. The origin of these remains obscure.

Owing to the deeply weathered nature of the porphyroid, mineralogical and chemical studies were not conducted.

The Sediments.

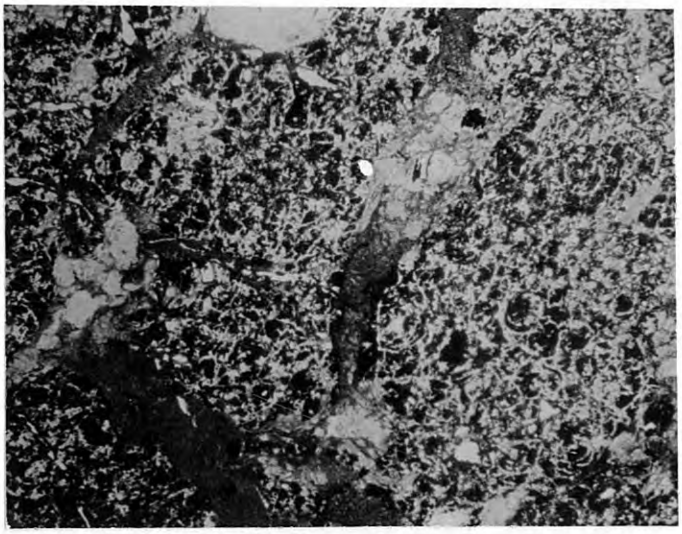
The sediments in contact with the quartz-feldspar porphyroid in this area vary from lithic and quartz greywackes to siltstones (possibly in part tuffaceous). These lithologies are ill-defined and grade into one another providing no marker horizons which can be easily traced throughout the outcrops.

The greywackes (in the sense of Pettijohn, 1957) are pale brown to grey, coherent rocks (Plate 16b), sometimes with bedd

Plate 15 (a) - well-preserved ash texture, Inset B Porphyroid (width of field - 2 mms; ordinary light).

Plate 15 (b) - hand specimen from Inset B area showing intimate intermixing of porphyroid with fine-grained wall rock (ruler graduated in 1/2 inches).

Plate 15 (c) - hand specimen from Inset B area showing megacrysts from the porphyroid isolated in wall rock (ruler graduated in 1/2 inches).




STRONG
455


STRONG
455

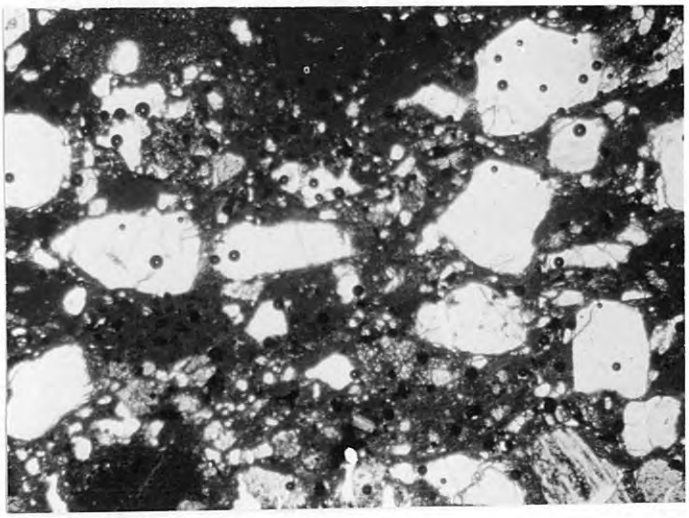
Plate 16 (a) - laminated siltstone.
(ruler graduated in 1/2 inches)

Associated sediments of the Inset B area.

Plate 16 (b) - greywacke.
(ruler graduated in 1/2 inches)

Plate 16 (c) - detail of greywacke fabric.
(width of field - 3 mms; ordinary light)


STANDARD POCKET ARMSTRONG
NO. RULEX 455



laminations ranging from about 1 cm. (specimen 431) to less than 2 mms. in thickness (specimen 405).

The fabrics of the rocks consist of open frameworks of quartz grains and rock fragments (specimen 431) or simply quartz grains (specimen 405, Plate 16c) set in a matrix of quartz and white mica(?). The clasts are generally angular to sub-angular with a complete range of sphericities and tend to be poorly sorted, although some grading (Plate 16b) and microcross-bedding is evident (specimen 405).

The rock fragments, up to 2.5 mms. long, commonly oriented in the cleavage surface consist of porphyroids, siltstones and cherts. Some of the quartz grains have fine-grained quartz mosaics attached, suggesting derivation from porphyroids. A little detrital white mica, feldspar and zirco are found.

The siltstones are coherent and thinly bedded in places with laminations in various shades of brown and red, the colou being the result of weathering.

In some cases (e.g. specimen 127), the laminations of coarser material (about 0.3 mms. thick) have numerous lobes, usually asymmetric, and lenses projecting downwards into the underlying finer-grained silt layer (Plate 16a). The lobes attain a thickness of up to 4 mms. and a length of just over 1 cm.; the lenses are much thinner but relatively elongate. Both show indications of internal lamination which can be seen to turn up at the edges of the structures. Where these structures are developed most, the inter-connecting layer appears attenuated between them, until only the merest remnant remains.

These textures are similar in nature to load structures described by Dzulynski and Walton (1965, p.143) and appear to be produced by the sinking of relatively coarse-grained, dense material into finer, less dense material.

The fabric of the siltstones consist of equant, sub-angular clastic quartz grains mostly separated by small white mica laths. A few tourmaline grains occur. The grain size of the material of the laminations alternates from 0.03 mm. to 0.01 mm.

Various Aspects of the Sediments.

The bedding attitude in the sediments varies locally, but generally strikes between N.E. and S.E. and dips westerly at shallow to moderate angles (Fig. 10).

The poor cleavage is expressed by a white mica(?)alignment in the matrices of the greywackes and siltstones and is parall to the foliation of the quartz-feldspar porphyroid (Fig.10).

The lithologies tend to be ill-defined and, in some place almost featureless, with poorly developed bedding which is visible on close examination, despite weathering, regular colo banding (probably due to staining) and cleavage development.

A typical feature of the sediments is the common occurren of irregular contacts due to intrusion and veining of coarser into finer material on the scale of an outcrop down to that of a hand specimen (e.g. specimen 432).

The most noticeable lithological contact is one between greywackes and underlying siltstones immediately to the west of Inset C shown in Fig. 10. The siltstone gives way to the greywacke with a series of thin bands (a few inches thick) of silt, which are intruded and in part disrupted by the coarser material (e.g. specimens 433, 467 and 468).

The porphyroidal body appears to intrude and terminate this greywacke-siltstone contact marked in Fig. 10 as G - S.

Contact Relationships of the Porphyroidal and Sedimentary Rocks.

In order to investigate the nature of the contacts betwee the two rock types, two areas containing the best exposures of the sediment-porphyroid contacts were mapped during a plane table survey and are represented by Inset C (on a scale of 20' to 1") and Inset D (on a scale 10' to 1"). The localities of these areas are given in Fig. 10.

Inset C.

The distribution of rock types in this area is illustrate in Fig. 11 which shows a limited part of the top (N.W.) contac of the quartz-feldspar porphyroidal horizon with the sediments as defined by Geopeko Ltd.

The main contact lies in the west of the mapped area represented in Inset C where sediments (unstippled legend) occurring to the west pass into quartz-feldspar porphyroid (stippled legend) to the east by way of a wide, gradational zone of intermixed porphyroidal and sedimentary material. Thi zone, which is about 100 feet wide, is referred to in Fig. 11 as the "zone of maximum contamination in porphyroid".

The contaminated zone consists of an intimate mixture of porphyroidal and sedimentary material (Plate 17), the latter decreasing in amount from west to east of the zone and being present as rafts and smaller inclusions ranging in size from 20 or 30 feet down to microscopic dimensions. Only inclusions of sediment greater than about 10 feet in size are represented on this map. The inclusions have irregular, indistinct edges and tend to have their larger dimensions approximately paralle to the trace of the foliation in the porphyroid.

The boundaries of this zone are somewhat ill-defined and are represented in Fig. 11 in approximate positions where the amount of contamination of one rock type by the other passes from widespread to small. The boundary of the relatively uncontaminated sediment and the intermixed zone is drawn as a sinuous, irregular trace to the west of which contaminated porphyroid is present only in small amount as irregular or pod-shaped bodies ranging from 5 to 30 feet in size.

To the east, the intermixed zone shows a gradual transiti

Figure 11.

Detailed geological map of Inset C area prepared by plane tabling.

___ · ___ · ___ eastern limit of zone of contamination of porphyroid by sediment.

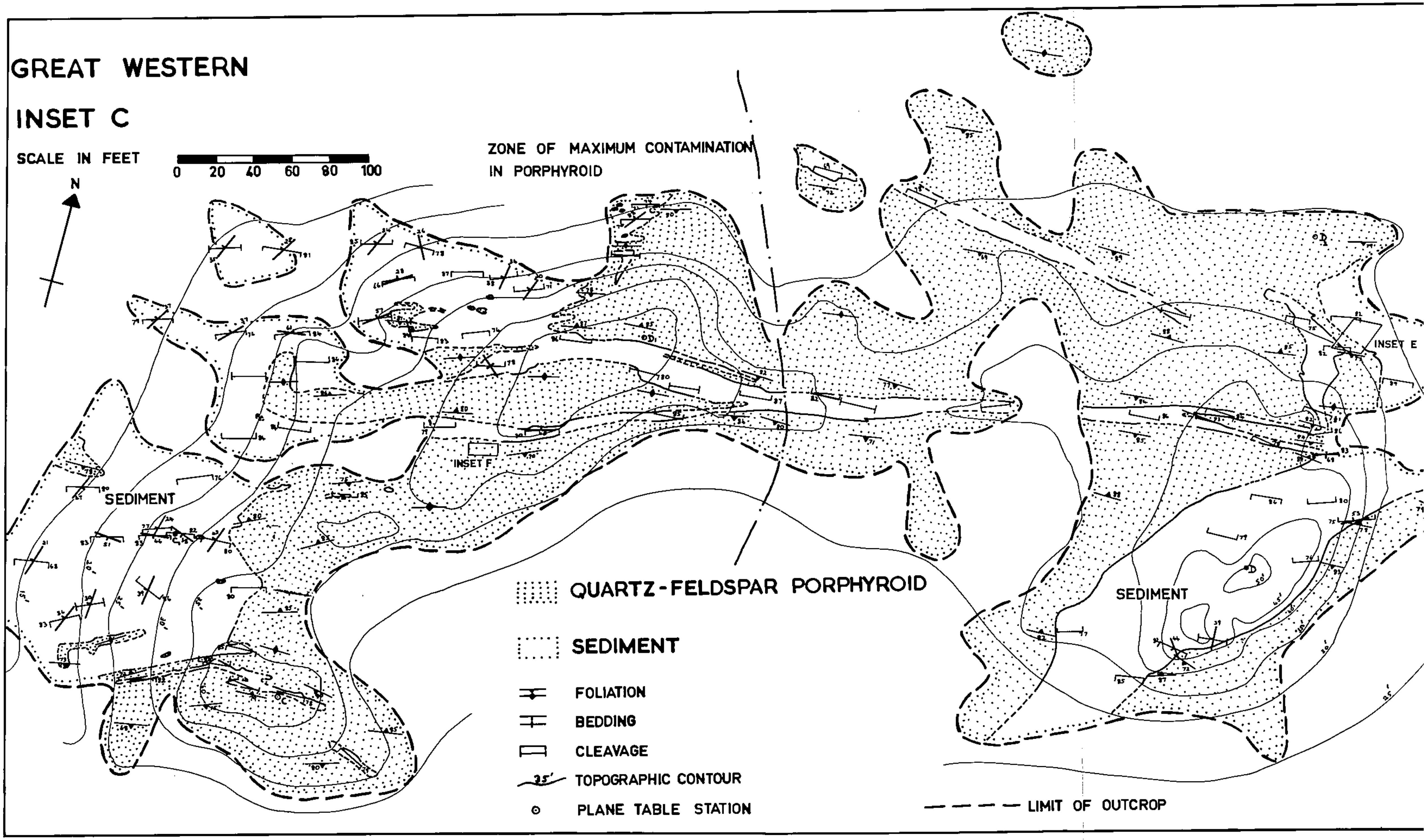
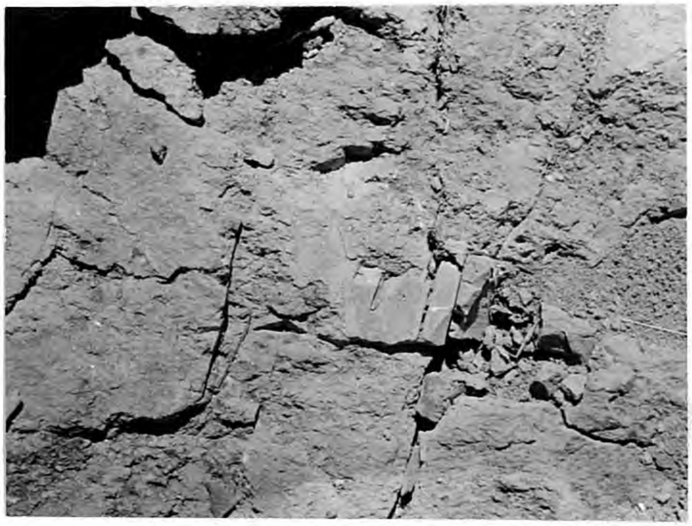

GREAT WESTERN
INSET C
SCALE IN FEET
0 20 40 60 80 100
N
ZONE OF MAXIMUM CONTAMINATION IN PORPHYROID
SEDIMENT
INSET F
INSET E
SEDIMENT
QUARTZ-FELDSPAR PORPHYROID
SEDIMENT
FOLIATION
BEDDING
CLEAVAGE
TOPOGRAPHIC CONTOUR
PLANE TABLE STATION
LIMIT OF OUTCROP

Plate 17 (a) - intermixed sediment and porphyroid.

General aspect of porphyroidal and sedimentary intermixing, Inset B.

Plate 17 (b) - sediment inclusion in contaminated porphyroid.
(width of field - one foot)



into uncontaminated quartz-feldspar porphyroid as the proportion of sedimentary material falls from widespread to nil.

A band of sediment trending N.E. - S.W. and approximately 80 feet wide occurs in the east of the area and has generally sharp, well-defined contacts as it contains little porphyroida material.

Two thin slivers of sediment, some 10 feet wide, the northern one at least 200 feet long with no visible connection to any other sediment body, the southern one about 400 feet in length virtually connecting the two bodies of sediment and bifurcating in places, traverse the porphyroid in an E. - W. direction.

No bedding or any other sedimentary structure was recognised in these thin bodies. The strike of the bedding in the sediments to the west is approximately N.E. - S.W. and in the same general direction as the few bedding attitudes obtained from the eastern band.

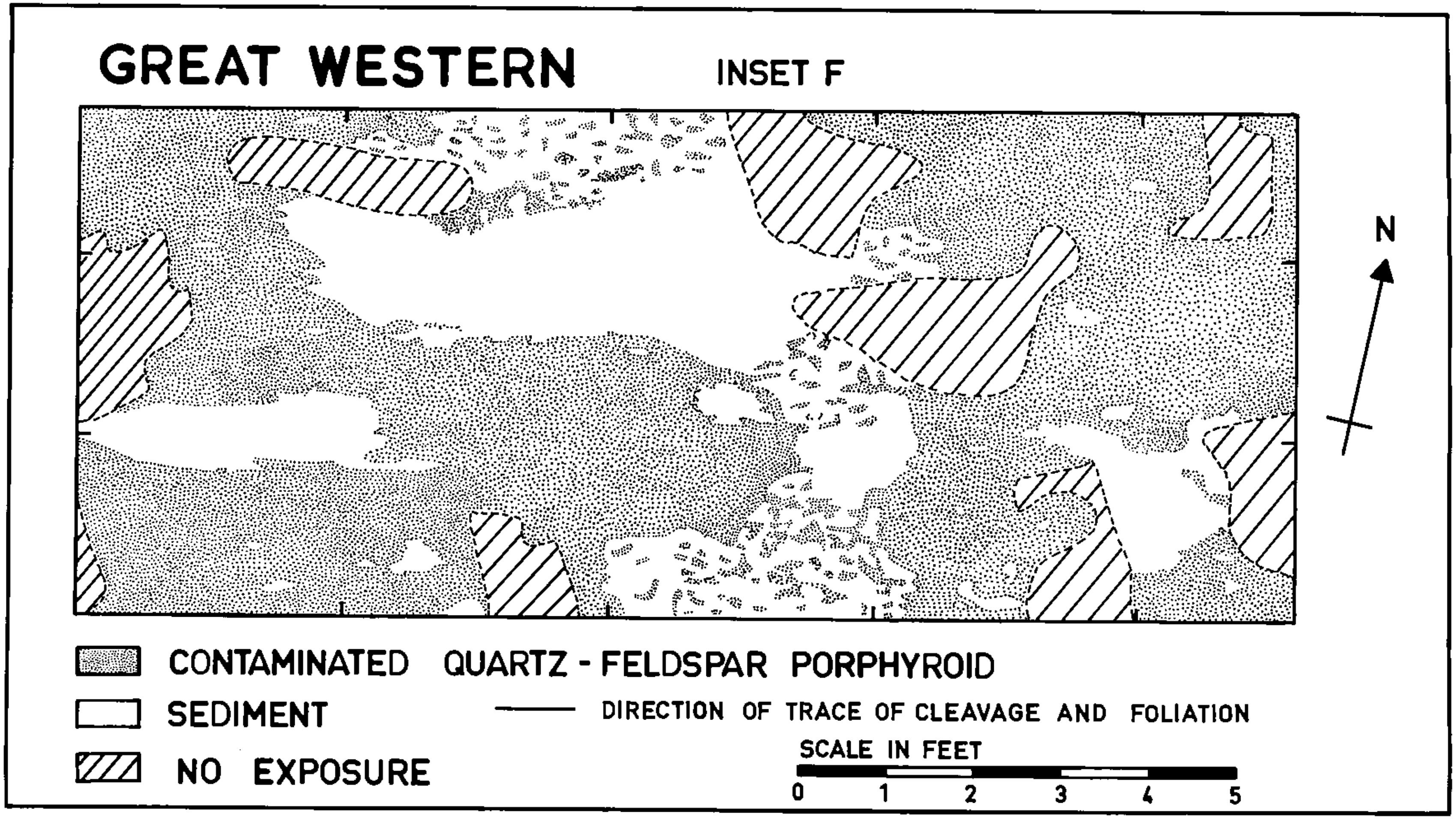
To illustrate the detail in outcrop of the intermixing in the contaminated zone, Inset F (locality in Fig. 11) was mapped on a scale of one foot to one inch using a reference grid and redrawn from photographs to give Fig. 12.

<u>Inset F</u>.

The two rock types represented are sediment and contamina quartz-feldspar porphyroid. The sediment patches are irregula

Figure 12.

Detailed geological map of Inset F area prepared by gridding and, in part, re-drawn from photographs.


GREAT WESTERN
INSET F
N
CONTAMINATED QUARTZ - FELDSPAR PORPHYROID
SEDIMENT
NO EXPOSURE
DIRECTION OF TRACE OF CLEAVAGE AND FOLIATION
SCALE IN FEET
0
1
2
3
4
5

in shape, although some tend to be elongate in the direction of foliation. The boundaries are indistinct as a result of the intimate association of porphyroidal and sedimentary material. The surrounding contaminated porphyroid contains sedimentary material in a scale too fine to be represented he

No bedding was found in any of the sedimentary inclusion

The cleavage in the inclusions appears similar in attitu to the foliation in the porphyroid.

Inset D.

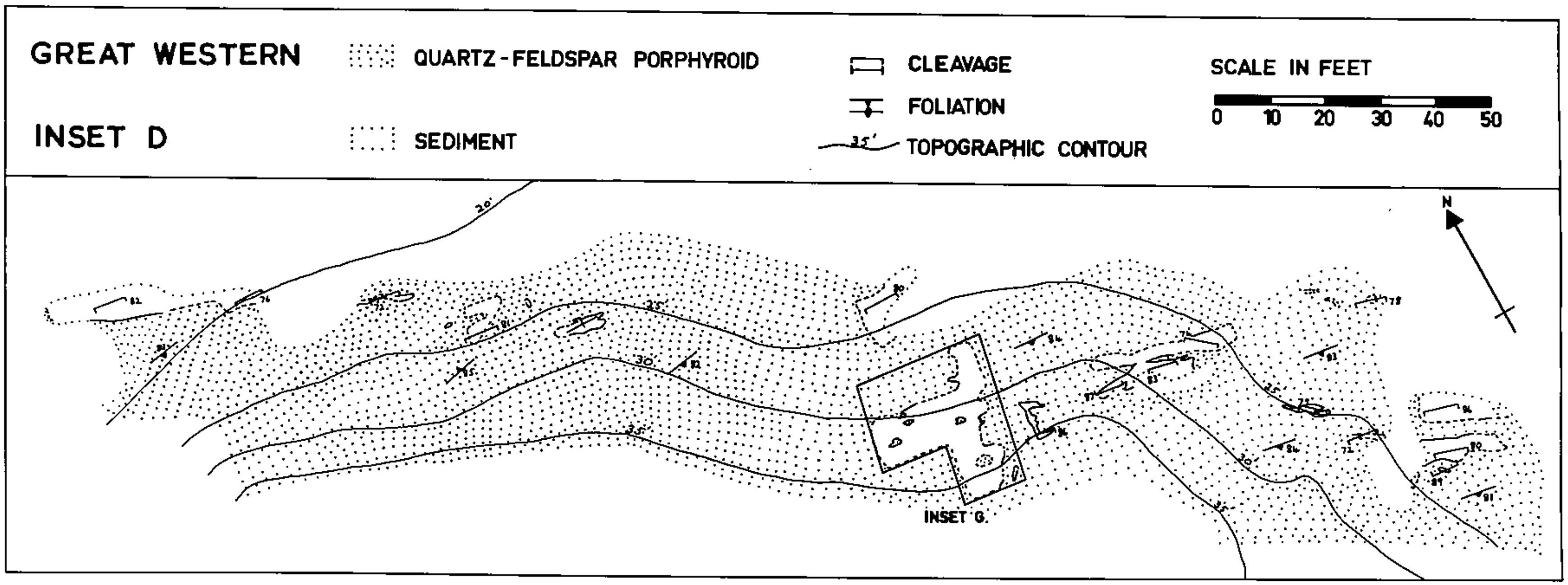
This area appears close to the bottom contact of the porphyroidal belt as defined during mapping by geologists of Geopeko Ltd.

A number of sedimentary rafts ranging from 30 to 40 feet in length with indefinite margins appear entirely surrounded by quartz-feldspar porphyroid (Fig. 13). There is a tendency for them to have their longer dimensions parallel to the trace of the foliation in the porphyroid. The cleavage surface in the sediment is similar in attitude to the porphyroid foliatio which, as usual, trends approximately E. - W. and is vertical to sub-vertical in inclination.

Some of these inclusions of fine-grained sediment possess a colour banding present in fine regular layers (e.g. specimen 1510, 498 and 495). On initial examination this banding was thought to be sedimentary bedding.

Figure 13.

Detailed geological map of Inset D area prepared by plane tabling.


GREAT WESTERN
INSET D
QUARTZ-FELDSPAR PORPHYROID
SEDIMENT
CLEAVAGE
FOLIATION
35' TOPOGRAPHIC CONTOUR
SCALE IN FEET
0 10 20 30 40 50
N
20'
35'
30
INSET G.

To examine the relationships in detail and to demonstrate the attitude of the banding in the included sediments, the largest of the rafts was mapped on a scale of 2' to 1" using a grid and the resulting map is reproduced as Inset G.

Inset G.

The colour banding in the sediments, although winding in detail, trends approximately N. - S., is sometimes vertical, but more often dips west or occasionally east. The dip of the bands vary from steep to shallow attitudes in close proximity.

Certain features of the banding, which became clear durin mapping, preclude its interpretation as sedimentary bedding.

These features are :-

(1) changes in width and sudden disappearances of the bands,

(2) no associated textural banding,

(3) in a few cases, two different directions of colour banding mutually transecting one another,

(4) in a few places where textural contrasts are visib the colour banding can be seen to run undeviated through the boundary (e.g. specimen 499).

The colour banding is best defined in the siltstones. Wh it occurs in coarse siltstones, greywackes and porphyroids, it can be detected only with difficulty, which causes the apparent truncation of the banding when it crosses a boundary from siltstone to coarser grained rock.

The banding most probably has its origin in the rhythmica precipitation of trace amounts of iron from solutions during t severe weathering of the rocks.

No occurrences of bedding have been recognised in the sediments of this area which are mainly siltstones and may on occasions show irregular contacts between material of slightly differing granularity. Hence, it was not found possible to determine the relation of sedimentary bedding to the porphyroi bodies.

As elsewhere, the geometry of the boundary of the sedimen and porphyroid is intricate in detail with pods and lenses of porphyroid in the sediment and sediment laths down to a few inches in the quartz-feldspar porphyroid (Fig. 14).

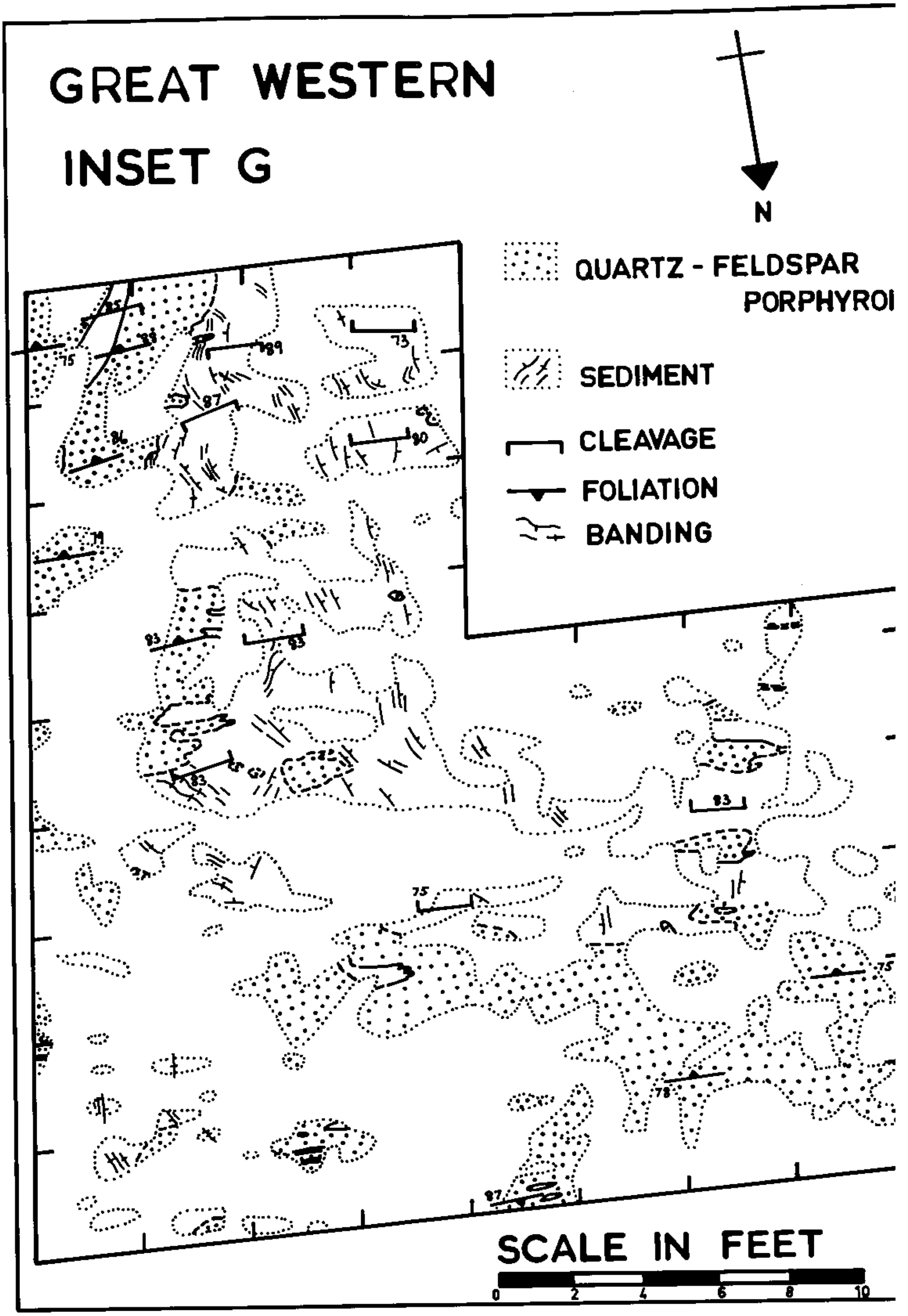
Aspects of porphyroid-sediment contacts at hand specimen and microscopic scales.

Intermixing at contacts between porphyroidal and sedimenta material persists down to the scale of a hand specimen (e.g. specimen 10) and even further to microscopic dimensions on occasions (e.g. specimen 7).

Tongues and veinlets of porphyroid penetrate into the sediments, the contacts being generally extremely sinuous and irregular (Plate 15b). In addition, the porphyroid contains isolated wisps and irregular diffuse patches of sedimentary material down to microscopic dimensions.

Figure 14.

Detailed geological map of Inset G area prepared by gridding.



GREAT WESTERN
INSET G
N
QUARTZ - FELDSPAR
PORPHYROI
SEDIMENT
CLEAVAGE
FOLIATION
BANDING
SCALE IN FEET
0
2
4
6
8
10

Fairly commonly, some of the porphyroidal megacrysts appear to have been forced bodily into the sedimentary phase (e.g. specimens 7 and 448). In some cases (e.g. specimen 434) complete incorporation of the megacrysts occur and they are isolated in a sedimentary groundmass (Plate 15c), in which adjacent megacrysts may be set in a thin skin of porphyroidal groundmass.

No obvious mineralogical or textural changes occur in the sediments at the contacts or in the enclaves or filaments with the porphyroid. There is a tendency, however, for these rocks to appear more compact (e.g. specimens 448 and 469) and to possess a subconchoidal fracture. This could be interpreted as a baking effect due to limited thermal metamorphism, but cannot be definitely substantiated.

3. THE BLACK EYE AREA.

The Black Eye Porphyroid.

In this area, two shallow drill holes, D.S. 5 and D.S. 6, have been completed in the quartz-feldspar porphyroid and thes help to document the extent of the body (Fig. 2).

Much of the exposed porphyroid is relatively fresh and ha a dark, massive appearance containing prominent megacrysts sitting in an aphanitic base.

Towards the north of the outcrop area, the degree of foliation increases and the rocks become red and deeply weathe Small, sedimentary inclusions occur infrequently, ranging up t a few centimeters in length and consist of chert and fine-grained sandstone. Quartz and white mica are the only minera[l] present in the enclaves and no feature of either the mineralo[gy] or texture can be directly attributed to thermal metamorphism.

Little information is available on the nature of the contacts of the porphyroidal body with the surrounding sedime[nts] or the exact extent of the body.

PETROGRAPHY.

In type and relative proportion of megacrysts, the Black Eye Porphyroid (Plate 18a) is very similar to the quartz-potassium feldspar-plagioclase porphyroid of the Warrego area (see Table 2) and the groundmass also has a relict, fragmenta[l] nature.

MINERALOGY.

The mineralogy and textures of the porphyroid are identi[cal] to those of the quartz-potassium feldspar-plagioclase porphyroid in the Warrego area (described above).

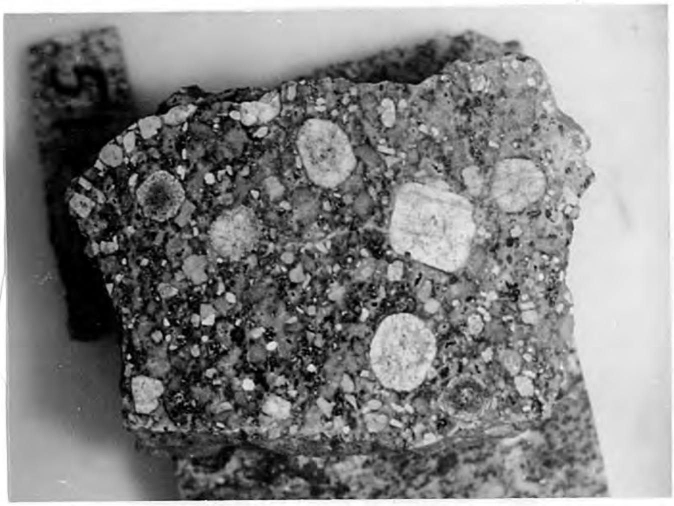
In specimen 478, green to purple patches occur up to 8 m[m] in size and contain a micaceous mineral arranged in a series of partial rosettes, the constituent laths of which have parallel extinction and are length slow. Across the laths, a[n] irregularly spaced, secondary cleavage or parting is present a[t] right angles to the main cleavage, which lies along the lengt[h] of the laths.

Plate 18 (a) - hand specimen of Black Eye Porphyroid (width of field - 5 inches).

Hand specimen representatives of quartz-feldspar porphyroids.

Plate 18 (b) - hand specimen of Creek Bed Porphyroid (width of field - 5 inches).


471



Pleochroism is slight (X - pale green or yellow; Y, Z - slightly darker green or yellow). The mica has a negati interference figure with a 2Vx of 34 ± 2^{o}.

From an X-ray powder diffraction pattern, the mica proves to be a 1M structural polymorph which can occur in muscovite, lepidolite and hydromica (A.A. Levinson, 1955) although the optic axial angle may be too large for a hydromi Some kaolinite was also detected (Appendix IV).

The patches containing this phyllosilicate may represent amygdaloidal areas.

4. THE GREAT WESTERN AREA.

The Great Western Porphyroid (s.s.)

The prominent foliation, present throughout the quartz-feldspar porphyroid in this area, strikes approximately east-west, is vertical to subvertical in attitude and is one aspec of the second phase of deformation in the region. It is distorted by the third phase of deformation with the product of chevron folds, kink bands and open warps often having brea along their axial surfaces which are normally steep. These folds are responsible for variations in the attitude of the foliation over areas ranging from a few inches up to tens of feet.

Little textural variation or stratification has been fou within the porphyroid in this area. Few inclusions of other types are present, although deep weathering makes detailed observations difficult. The contacts with the enclosing sedimentary rocks are nowhere visible and the exact shape of the body is unknown.

Two thin, deeply-weathered dykes of lamprophyre occur cutting the porphyroid.

Despite weathering and iron staining, the porphyroid can be recognised as petrographically equivalent to the Warrego Porphyroid already described. The typical habits of the three megacryst phases, potassium feldspar, quartz and plagioclase, are still distinctive in a red, almost aphanitic groundmass. The large ovoid grains tend to disintegrate leaving cavities, while the smaller quartz grains protrude from the rock faces giving the porphyroid a very coarse crumbling appearance.

Microscopically, both potassium feldspar and plagioclase are found to be pseudomorphed by white mica, the large K-feldspar ovoids being composed of aggregates of unorientated laths, while each plagioclase grain is commonly replaced by on large lath whose cleavage may be distorted by micro-flexures. Quartz remains unaltered and makes up most of the groundmass along with white mica which is masked by red limonite.

Fragmental textures, similar to those described in the matrix of the Warrego Porphyroid are present in some of the groundmasses at Great Western.

The white mica pseudomorphs after plagioclase have a negative interference figure with a 2Vx of $36 \pm 2^{\circ}$. Their

X-ray powder diffraction pattern, which was not examined for possible paragonite content, identifies them as the $2M_1$ structural polymorph of muscovite (see Appendix IV).

<u>Metamorphic grade</u>

The mineral assemblages present in the rocks of the Warrego area are typical of the lower greenschist subfacies (quartz-albite-muscovite-chlorite, Turner and Verhoogen, 1960) of regional metamorphism. These are -

a) quartz-muscovite-chlorite in the phyllites and quartz porphyroids, and

b) quartz-albite - muscovite-chlorite-potassium feldspar in the quartz-feldspar porphyroids.

Albite is consistent with this grade of metamorphism although the plagioclase may have been albite prior to regiona metamorphism (see Chapter 8). The presence of some green-brown biotite, most of which is altered to chlorite, in the above assemblages suggests that the metamorphism at its peak may have approached middle greenschist facies (c.f. Noble, 1966). Whether any wall rock alteration connected with nearby sulphide mineralization has contributed to these mineral assemblages is unknown.

Weathering conceals the nature of the mineral assemblages present in the other occurrences except for the wall rocks at the Inset B area which are virtually unmetamorphosed having a poorly developed slaty cleavage expressed as an alignment of traces of white micaceous material.

Nature of the Great Western Porphyroid (s.l.)

Summary.

The quartz-feldspar porphyroid is the only rock type whic is known to be common to all of the areas - Great Western, Black Eye, Inset B and Warrego.

The main primary megacryst assemblage present is quartz, potassium feldspar and plagioclase (or pseudomorphed equivalen In the Warrego Porphyroid, this gives way to an assemblage in which plagioclase is absent, but this may be a secondary featu resulting from the obliteration of plagioclase by alteration o metamorphism.

Within the full assemblage of quartz, potassium feldspar and plagioclase, modal analysis shows that, for the Warrego Porphyroid, the individual mineral types are not present in strictly constant amount, although they fall within relatively narrow limits (the sum occurring between 28% and 41%). There no sign of any stratification in the megacryst distribution.

On careful examination, textural patterns may be seen within the groundmasses of the rocks and indicate that the matrices were once composed of a close-packed arrangement of volcanic glass shards. This evidence of a vitroclastic nature for the original groundmass identifies the origin of the quart feldspar porphyroids as volcanic pyroclastics.

The original shards are never distorted into a streaky, directed texture in any orientation other than that of the foliation. Hence, if primary distortion of shards into a eutaxitic texture may be taken as an indication of welding, the fragments in these pyroclastics, although close-packed, are unwelded, or at most show incipient welding in places.

Welding is confirmed only in a few cases where perlitic crack patterns cut across the fragmental shapes in the matrix indicating that some parts of the groundmass behaved as a homo geneous glass. Except for this evidence of welding and occasional patches of groundmass containing infilled vesicles, the shards show little capacity for heat retention. The best preserved relict textures tend to occur at the contacts of the porphyroids (e.g. Hole 5, specimen 94, plate 2c). No thermal effects are noted in the adjacent country rocks.

Few volcanic rock fragments are visible in these rocks.

The nature of the contacts of the pyroclastics has been demonstrated in the Inset B and Warrego areas. No erosional features have been recognised on any of the contacts which are marked by a zone of mutual contamination, the intimate nature of which infers that the rocks were unconsolidated when the intermixing took place. The mutual contamination occurs on th scale of an outcrop (see Fig. 11) down to microscopic dimensio

The pyroclastic appears to have locally intruded and truncated the stratigraphy of its containing rocks (e.g. the greywacke-siltstone contact, Inset B, Fig. 10), in places leaving thin stringers of wall rock as remnants (e.g. Inset C, Fig. 11), and wholly or partially isolating rafts of wall rock close to the contact, producing a banded effect (e.g. Warrego core sections).

In this connection, it is impossible to assess in detail the contribution of the tectonic deformation in controlling the distribution of the porphyroid and tectonic sediment as mapped at Inset C (Fig. 11) for example. Due to the difficult in recognising and tracing sedimentary bedding, no information is available on the mesoscopic effects of the deformation and hence it is impossible to restore the pre-folding attitudes an shapes of the porphyroid-sediment relationships. However, deformation must be responsible for the strong E.-W., sub-vert orientation of these inclusions and rafts of wall rock paralle to the regional tectonic surface.

Discussion.

The four main areas of quartz-feldspar porphyroids may form, or be part of, a poorly exposed, grossly conformable horizon situated in Warramunga Group rocks and extending for a strike length of some 12 miles. The actual continuity of the horizon is based on :

1) surface mapping of poor exposures,

2) the presence of float of appropriate type, and

3) the identification of weathered rubble recovered by a series of auger holes.

The exact thickness of the pyroclastic is unknown as no complete section is exposed in any one area. As suggested before, it could be as much as 1,500 feet, although this thickness could be made up of several members of the same rock type, despite the fact that no internal contacts have been recognised in any of the quartz-feldspar porphyroidal occurrences.

The top contact may be represented in the Inset B area and the bottom one in the Warrego area.

The substantial extent of the horizon considered with the lack of bedding and original vitroclastic groundmass suggests an ash-flow origin for the quartz-feldspar porphyroid.

The general absence of welding of the shards in the quart feldspar porphyroid and the lack of thermal metamorphic effect in the containing wall rocks are consistent with rapid cooling of the system under extrusive or high-level conditions.

The poor outcrop, in conjunction with the metamorphism an deep weathering in this region, conceals details of stratigrap which are often essential in determining the exact conditions deposition of pyroclastic horizons, e.g. whether subaerial or subaqueous.

Originally it was considered that ash flows could only fo subaerially (Ross and Smith, 1961; Beavon, Fitch and Rast, 196

Recently, however, various workers have recognised ash flows of subaqueous origin and have been considering criteria for their distinction from subaerial varieties (Mutti, 1965; Fisk and Matsuda, 1964).

In this respect, several features seem worthy of mention.

a) Welding.

The incipient welding in the groundmass of the Great Western Porphyroid (s.l.) is not diagnostic of a subaerial or subaqueous origin. Light, incipient welding has been documented from ash flows considered to be submarine by Mutti (19 and not all subaerial varieties show heavy welding (Beavon, Fitch and Rast, 1961 and Ross and Smith, 1961).

b) Ash content.

According to Fiske and Matsuda (1964), land deposited as flows almost always contain more than 50% ash, which is the ca with the Great Western Porphyroid (s.l.), while subaqueous pyr clastic flows studied by them feature only 10% to 25% ash.

c) Thickness.

Whereas the thickness of subaqueous ash flows tends to be measured in tens of feet (Mutti, 1965; Fiske and Matsuda, 1964 those of subaerial origin may reach hundreds of feet in thickn (Branch, 1967), the latter being more a feature of the Great Western Porphyroid (s.l.).

d) Asociated rocks.

The greywackes recorded in the sediments in association w the Great Western Porphyroid (s.l.) are poorly sorted and occasionally feature graded bedding, micro-cross bedding and slumping with veining and disruptions of finer-grained layers and are typical of those recorded by Dunnet and Harding (1965) and Elliston (1965) in the Warramunga rocks. They appear typical of sediments deposited in moderate to deep water conditions by turbidity currents. The close association of the pyroclastic horizon with these sediments suggests that the pyroclastics are subaqueous, unless it indicates subaerial deposition of the latter during periods of rapid emergence.

e) Contacts.

The intimate intermixing and interbanding between the pyroclastics and wall rocks and, in some cases, local intrusio of the stratigraphy of the former by the latter must have take place while the rocks were unconsolidated. This would have appeared to have occurred either during slumping due to instability of, or as a result of the build up of high pore pressures in the pyroclastic during loading of the pyroclastic sedimentary sequence. Both mechanisms would require a water-saturated sequence which could be realized by either original subaqueous deposition of all members or subaerial deposition of the pyroclastic followed by re-submergence. The incipient welding shown by the Great Western Porphyroid (s.l.) would not be expected to prohibit to any great extent the loss of cohesi among the bulk of the vitroclastic fragments necessary to achi remobilization of the pyroclastic.

In conclusion, the Great Western (quartz-feldspar) Porphyroid (s.l.) may be considered as a pyroclastic horizon of ash-flow origin, the product of a fluidized magma in which volcanic fragments are transported in gaseous suspension. Whether the environment of deposition is subaerial or submari has not been satisfactorily resolved.

While the welding, the associated rocks and the contacts are not diagnostic of origin, the thickness and ash content of the pyroclastic favour a subaerial origin, although the evidence is not compelling.

Associated Rocks.

The environment of deposition of the other pyroclastics (quartz porphyroids and fine-grained phyllites) recorded in th Warrego drill cores (the exposures in the other three main are allow little possibility of establishing the continuity of the pyroclastic rocks) is also in doubt although, as they are inte banded with volcanic greywackes (the relatively coarse-grained phyllites), they are probably subaqueous. No evidence of welding occurs in any of these rocks.

The fine-grained phyllites or ash deposits have no visibl features relating to mode of origin. The extremely variable

distribution of the quartz megacrysts, the poorly sorted natu
and the lack of bedding of the quartz porphyroids, suggests that, if subaqueous, they have been deposited by mud-flow rat than turbidity current action.

The lack of correlation of the quartz porphyroid interse tions among the drill holes indicates that the bodies are present as discontinuous lenses, or as bands of rapidly varyi thickness. This indefinite and non-continuous stratigraphy be either a depositional feature or due to post depositional slumping.

The presence in the greywackes of porphyroidal rock fragments infers that the former derived at least some material from existing pyroclastics or other volcanic rocks and in fac some of the pyroclastics described above may contain, or owe their origin to material reworked from previous pyroclastics as a result of slumping.

If the quartz porphyroids, ash deposits and volcanic gre wackes recorded in the Warrego area form an essential part of the Great Western Porphyroid (s.l.) then this pyroclastic horizon will consist of several porphyroidal bands and, as su may be comparable to other porphyroidal horizons in the Tenna Creek area. The Bernborough Formation in the north, for exam consists of three porphyroidal bands (each about 600 feet thi with interbedded shales and siltstones, the whole association totalling 3,000 feet in thickness according to Dunnet and Har ing (1965).

They consider the bands to be a series of tuffs, ash beds and massive volcanic greywackes formed as ash flows or by the redistribution of fragmental volcanics, such as subaqueous ash and crystal tuff deposits, by mud-flow or turbidity current action, i.e. a generally similar origin to that proposed for the Great Western Porphyroid (s.l.).

Alternative Explanation.

An alternative explanation of the nature of the Great Western Porphyroid (s.l.) is possible, although less likely. The poor exposures and sparse evidence of extent allow the possibility that the quartz-feldspar porphyroidal body may be a steeply dipping structure, such as a fissure filling and further may be continuous, discontinuous, or, in the extreme case, a line of at least four separate volcanic vent fillings. The fragmental textures characteristic of the matrices of the quartz-feldspar porphyroids indicate that the magma was intruded in a fluidized condition (c.f. Branch, 1967). In this explanation, the intermixing and interbanding in the porphyroidal-wall rock contacts may be attributed to intrusion of fluidized magma through unconsolidated sediments and pyroclastics.

CHAPTER 4.

THE CREEK BED PORPHYROID.

Several small bodies of quartz-feldspar porphyroid occur within, and near, the south-west portion of the Station Hill Granite (Fig. 17). In order to determine their nature and th relationship to the adjacent granite rocks, the largest and best exposed porphyroidal body was mapped using a plane table and is represented in Fig. 15 where it is referred to as the Creek Bed Porphyroid (map reference 2,549,200 N; 186,000E).

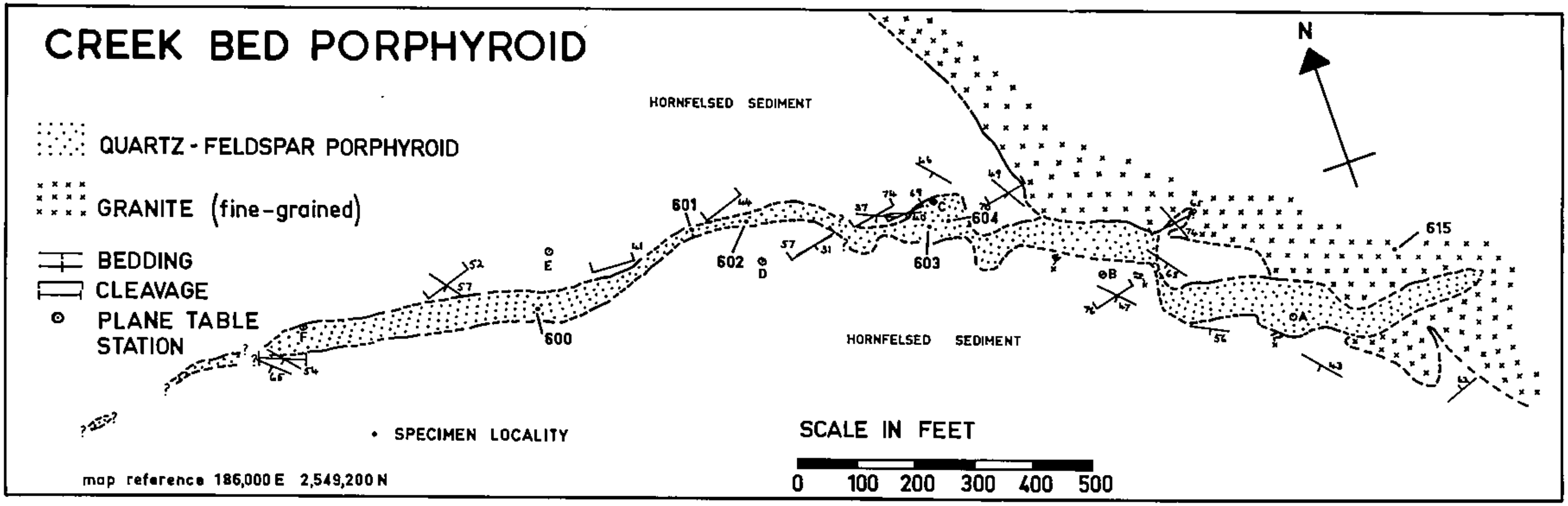
It is present as a thin band running in an east-west direction, varying in thickness from 20 to 50 feet (Fig. 15). Along most of its length (approximately one half mile), it is enclosed in metasediments within which it tapers out to the west. In an eastward direction, the porphyroidal body crosse the granite-metasediment boundary and terminates some 200 fee inside the granite. A few hundred feet to the east, in the direct line of the outcrop, several strips of similar porphyr occur isolated within the granite and appear to represent portions of the Creek Bed Porphyroid.

No information is available on the attitude of the porphyroidal body with depth. In its east-west trace, the porphyroid is transgressive to the bedding of the enclosed metasediments which strikes north-west and dips to the south-west away from the granite.

The contacts between the porphyroid and the metasediments

Figure 15.

Detailed geological map of the Creek Bed Porphyroid prepared by plane tabling.


CREEK BED PORPHYROID
QUARTZ - FELDSPAR PORPHYROID
GRANITE (fine-grained)
BEDDING
CLEAVAGE
PLANE TABLE STATION
• SPECIMEN LOCALITY
map reference 186,000 E 2,549,200 N
HORNFELSED SEDIMENT
HORNFELSED SEDIMENT
N
600
601
602
603
604
615
A
B
C
D
E
F
SCALE IN FEET
0 100 200 300 400 500

where exposed, appear sharp. No inclusions of wall rock have been found within the porphyroid. The contacts between the porphyroid and the granite are not visible.

The <u>metasediments</u>, in which bedding is difficult to see, are indurated hornfelses situated in the contact aureole of th Tennant Creek Granite Complex. They possess an incipient east west cleavage which tends to be sub-vertical or to dip to the north. In general terms, the hornfelses of the granite comple have been described by Whittle (1966) and Crohn and Oldershaw (1965) as recrystallized shales, slates or siltstones.

No comprehensive study of the hornfelses was attempted an the few specimens selected from this area for thin section examination proved to be volcanic ashes, recrystallized to spotted biotite hornfelses which still exhibit distinct, fragmental ash textures.

The <u>granite</u>, (represented by specimen 615, phase C) in th area is a cream-white, massive, medium-grained, slightly "porphyritic" rock bearing enough micrographic intergrowth to be termed a granophyre (Table 16).

PETROGRAPHY.

The Creek Bed Porphyroid is very similar to the Warrego a Black Eye representatives having a slightly greater volume ($>$ 40%, Table 2, in which Creek Bed (A) specimens are from the porphyroidal body as mapped in Fig. 15 and Creek Bed (B) specimens were selected from one of the strips of porphyroid isolated in the granite), of the megacrysts potassium feldspar, quartz and plagioclase sitting in a fine-grained groundmass (Plate 18b). As before, the large feldspa grains are present in distinctly greater volume than either of the other two constituents.

A significant difference, however, does occur in that mos of these large feldspar megacrysts are composed of plagioclase although in some cases, (e.g. specimen 602) grains of both plagioclase and potassium feldspar occur as large megacrysts in the same rock.

The occurrence of plagioclase having the characteristic habit and honeycombed, embayed aspect typical of the potassium feldspar in the other porphyroidal rocks is taken to indicate that the plagioclase has replaced most of the potassium feldsp grains. Of the thirteen large grains selected at random from the Creek Bed rocks, only one consisted of potassium feldspar, eleven were wholly plagioclase and one consisted of potassium feldspar with coarse veins of plagioclase having chess-board twin patterns. This last relationship may be considered as an intermediate stage in the complete transformation of potassium feldspar to plagioclase.

In other instances (e.g. specimen 600), the large megacry are masked by ferromagnesian material, mainly biotite or chlor

The Matrix.

The matrix of the Creek Bed Porphyroid is coarser in grai than that present in the Warrego and Black Eye Porphyroids. I is composed mainly of a granular mosaic (0.1 mm. in grain size of quartz and feldspar with minor biotite and white mica patch and also shows incipient development of spherulites. The shap and fragmental ash particles are visible in the groundmass bei preserved in spite of recrystallization (e.g. specimen 600 and 601).

In some cases, (e.g. specimen 602), the groundmass textur become dominated by spherulites up to 1.5 mms. in diameter consisting of radiating fibres of potassium feldspar (Plate 19 All megacrysts, regardless of composition, have almost complet fringes, up to 0.8 mms. in thickness, of these fibres. The interstices of the spherulites contain mosaics of quartz and feldspar (mainly plagioclase) with some biotite and chlorite.

Thin laths of biotite (up to 0.1 mm. long) occur througho the groundmass, some having a random orientation while others radiate from a point. They are often of rapidly varying width and have the appearance of microlites or acicular crystals common in volcanic glass.

MINERALOGY OF MEGACRYST PHASES.

1. POTASSIUM FELDSPAR.

As already mentioned, potassium feldspar is of limited

Plate 19 (a) - chess-board twinning in albite, (width of field - 1-1/2 mms; crossed polars).

Textural details of the Creek Bed Porphyroid.

Plate 19 (b) - embayment in potassium feldspar pseudomorphed by plagioclase.
(width of field - 3 mms; ordinary light)

Plate 19 (c) - spherulitic textures in groundmass.
(width of field - 3 mms;)

occurrence in the large feldspar megacrysts due to its replacement by plagioclase. The single representative recorded in detail is similar to the Black Eye and Warrego (Group 1) potassium feldspars, with an optic axial angle 2Vx of 77 to 80° and an X-ray obliquity of 0.83, but has a bulk composition richer in Ab + An at 33 mol. % determined by the X-ray diffraction method.

2. PLAGIOCLASE.

Texture.

Plagioclase feldspar is present in megacrysts of two different sizes and habits.

a) The large grains pseudomorphous after potassium feldspar are generally similar in size and shape to those present in the other porphyroids, except that there is apparently an absence of fractured grains which are fairly common in the Warrego and Black Eye occurrences. The embayments and internal cavities, while being preserved in the plagioclase, are ill-defined and, in some cases, are represented by thin, discontinuous trails of inclusions (Plate 19b). The mineralogy in the cavities show no remarkable textures and consists of fine, intergrowth patterns of quartz and feldspar with some chlorite aggregates in places.

The plagioclase of this textural modification is eith untwinned, or has a chess-board twin pattern (Plate 19

b) The small plagioclase grains are similar in habit, siz and twin patterns to those of the Warrego and Black Ey Porphyroids.

Optical and X-ray determination.

Information on the attitude of the optical indicatrix arrived at by the method of Rittmann and El-Hinnawi (1961, Appendix III) in addition to measurements of the optic axial angle (2Vx) and of the separation of appropriate X-ray peaks (Table 9) as carried out on the plagioclase of the other porphyroids, reveals that the plagioclase of the Creek Bed Porphyroid relates to the high-order curves.

Composition.

The composition of the plagioclase in both textural occurrences deduced from the orientation of the optical indica as above, is in the albite range (Table 9).

X-ray fluorescence analysis of a separate of the plagioclase from the large megacrysts present in the Creek Bed Porphyroid (specimen 606) confirms that the feldspar is albite, the orthoclase content being 3.7 mol. % and that of rubidium, strontium and barium being 16, 36 and 77 p.p.m. respectively (Table 4).

A separate of the small plagioclase grains from the same specimen (606) was measured by emission spectrography (Appendi IX) and recorded values for strontium and barium of 20 p.p.m. a

TABLE 9.

Optical and X-ray data on plagioclase from the Creek Bed Porphyroid.

Specimen	$2Vx^{o}$	X-ray peak separation $131-1\bar{3}1$	$\bar{1}32-131$	Composition by optics.		
A.						
600 (1)	91-92	-	-	-	LM	An_6
600 (2)	92-98	-	-	An_1	LM	
600	96-104	1.10	2.75	An_5	M	
601(a)	89-92	1.15	-	-	LM	
601(b)	100-107	-	-	-	LM	
601(b2)	86-90	-	-	-	LM	
601	94-96	1.17	2.70	An_6	M	
602(b)	90-99	-	-	-	LM	An_3†
602(c1)	88-90	-	-	-	LM	
602(c2)	96-101	-	-	-	LM	
B.						
605(a)	95-103	1.09	-	An_5	LM	
605(b)	93-98	1.09	-	-	LM	
605	98-100	-	-	An_4	M	
606(a)	98-107	-	-	An_6	LM	
606(b)	95-101	1.10	-	An_3	LM	
606	96-101	-	-	An_3	M	

M - megacrysts, LM - large megacryst

† - normative value.

150 p.p.m. respectively.

3. QUARTZ.

In size and shape the quartz grains are similar to those already described from the other porphyroids, having typical embayments and internal cavities.

4. BIOTITE.

A few embayed, irregular, bleached biotite grains up to 0.8 mms. in size are present, altering to chlorite along the cleavages. A few mafic patches of a similar size are made up different combinations of biotite, chlorite, epidote, allanite sphene and magnetite.

Nature of the Creek Bed Porphyroid.

The shape of this porphyroidal body is relatively well-defined when compared with the Great Western Porphyroid. With a width varying between 20 feet and 30 feet, a substantiated length of about half a mile, and, considering that it is transgressive to the bedding in the wall rocks, the porphyroid is probably a dyke or fissure filling. The relict, fragmental asl textures preserved in the groundmasses indicate that the magma was introduced in a fluidized condition. The poorly exposed rock contacts appear sharp, suggesting that the wall rocks wer consolidated at the time of intrusion. Because the contacts between the porphyroid and the granite are not exposed it is not possible to determine an order of intrusion, however the fact that discontinuous strips of quartz-feldspar porphyroid are found in the granite just to the east, suggests that the granite has disrupted the porphyroidal body and is therefore later. The relatively coarse grain of the matrices of this porphyroid, when compared to the Warrego Porphyroid, for example, may then be attributed to thermal metamorphism by the granite.

CHAPTER 5.

CHEMISTRY OF THE QUARTZ-FELDSPAR PORPHYROIDS.

Major element composition.

Major element analyses and Barth mesonorms of twelve qua: feldspar porphyroids are presented in Table 10 where they are comprised of eight Warrego, two Black Eye and two Creek Bed samples.

It is immediately apparent that, in composition, the quartz-feldspar porphyroids form a closely related series in which the most significant variation is in their alkali conte:

On a petrographic basis (see Chapter 3), it is possible to divide the quartz-feldspar porphyroids into two groups -

A) which includes those rocks with the full megacryst assemblage of quartz, potassium feldspar and plagioclase of their alteration products (i.e. Warrego specimens 51, 61, 87, 401 and 94; Black Eye specimens 480 and 477 and Creek Bed specimens 600 and 602), and

B) which includes those rocks whose petrography indicate the possibility that they may not be altered from roc! having the complete megacryst assemblage (i.e. Warreg specimens 12, 35 and 249).

This grouping is also reflected in the major element com sition of the rocks, mainly in the alkali contents.

The members of Group A are characterised by having

TABLE 10.

Major element compositions and molecular norms of Tennant Creek rocks - quartz-feldspar porphyroids.

Specimen nos. - group A

Warrego area

51	
61	quartz - potassium feldspar
87	- plagioclase porphyroids
401	
94	as above (with K-feldspar pseudomorphed by plagioclase)

Black Eye area

480	quartz - potassium feldspar
477	- plagioclase porphyroids

Creek Bed area

600	quartz - potassium feldspar - plagioclase porphyroids
602	(with K-feldspar in part pseudomorphed by plagioclase)

Specimen nos. - group B

Warrego area

35	quartz - potassium feldspar porphyroid
12	as above (K-feldspar pseudomorphed by white mica)
249	as above (quartz pseudomorphed in part by chlorite)

ANALYSES AND MOLECULAR NORMS OF TENNANT CREEK ROCKS

			Porphyroids		Warrego				Black Eye		Creek Bed	
Specimen	51	61	87	401	12	35	94	249	480	477	600	602
SiO_2	72.81	73.93	72.97	73.49	73.05	73.98	69.77	55.57	72.50	72.66	72.68	73.70
TiO_2	0.37	0.35	0.36	0.35	0.36	0.35	0.44	0.57	0.43	0.43	0.49	0.47
Al_2O_3	13.05	13.06	13.09	12.52	12.70	12.86	15.02	20.26	13.43	13.48	13.90	13.47
Fe_2O_3	0.76	0.48	1.06	0.00	2.55	1.45	0.92	1.37	1.20	1.26	1.08	1.21
FeO	1.79	1.86	1.83	3.17	3.08	2.79	2.43	2.76	1.67	1.72	1.36	0.97
MnO	0.08	0.08	0.09	0.10	0.10	0.12	0.19	0.05	0.04	0.03	0.02	0.03
MgO	1.10	0.87	0.90	1.38	1.37	1.18	1.11	3.68	0.55	0.80	1.11	0.60
CaO	0.22	0.25	0.17	0.19	0.06	0.09	1.01	0.11	0.32	0.15	0.74	0.40
Na_2O	2.09	1.34	1.30	2.14	0.11	0.52	4.72	0.76	3.55	3.15	5.63	4.83
K_2O	7.10	7.38	6.80	5.68	4.46	5.00	2.76	12.36	4.85	5.50	1.51	3.17
P_2O_5	0.06	0.07	0.07	0.09	0.09	0.08	0.11	0.13	0.09	0.06	0.09	0.13
Ign. Loss	1.35	1.10	1.24	1.78	2.13	2.40	1.22	3.00	1.00	1.07	0.87	0.61
H_2O^-	0.09	0.09	0.16	0.07	0.07	0.17	0.09	0.17	0.11	0.15	0.12	0.17
Total	100.87	100.86	100.04	100.96	100.13	100.99	99.79	100.79	99.74	100.46	99.60	99.76
					Mesonorms							
Q	31.41	35.71	37.78	37.31	54.81	50.67	28.14	3.60	37.17	31.33	30.74	30.96
Or	37.81	40.00	37.25	26.46	21.58	24.83	10.60	62.11	26.03	29.26	4.65	16.45
Ab	19.20	12.35	12.15	19.75	1.05	4.95	43.10	6.95	26.70	28.85	51.15	43.95
An	0.70	0.75	0.35	0.35	0.00	0.00	4.35	0.00	1.05	0.35	3.10	1.15
C	1.87	2.91	3.94	3.07	8.98	7.60	2.99	6.24	2.19	2.48	2.08	1.85
bi	8.06	7.60	7.20	12.86	10.58	10.18	9.60	19.42	5.38	6.32	6.96	4.08
mt	0.81	0.51	1.16	0.00	2.85	1.61	0.98	1.46	1.29	1.35	1.14	1.27
ap	0.13	0.16	0.16	0.19	0.10	0.14	0.24	0.18	0.19	0.13	0.19	0.27
ΣQ+Or+Ab	88.42	88.06	87.18	83.52	77.44	80.45	81.84	72.66	89.90	89.44	86.54	91.36

Analysed by D. McP. Duncan

a) an almost constant amount of total alkalies, $K_2O + Na_2O$, ranging from 7.14 to 9.19% although ther is a slight increase in that value with increase in K_2O (Fig. 16) and consequently

b) an inverse relationship in content of K_2O when compa with that of Na_2O giving a wide range in alkali rati (Table 11).

Hence, the two Creek Bed samples along with one from Warrego (specimen 94) have a high sodium to potassium ratio (Fig.16), while the remaining Warrego specimens in this group (specimen 61, 51, 87 and 401) have low ratios relative to those of the Black Eye samples (specimens 480 and 477).

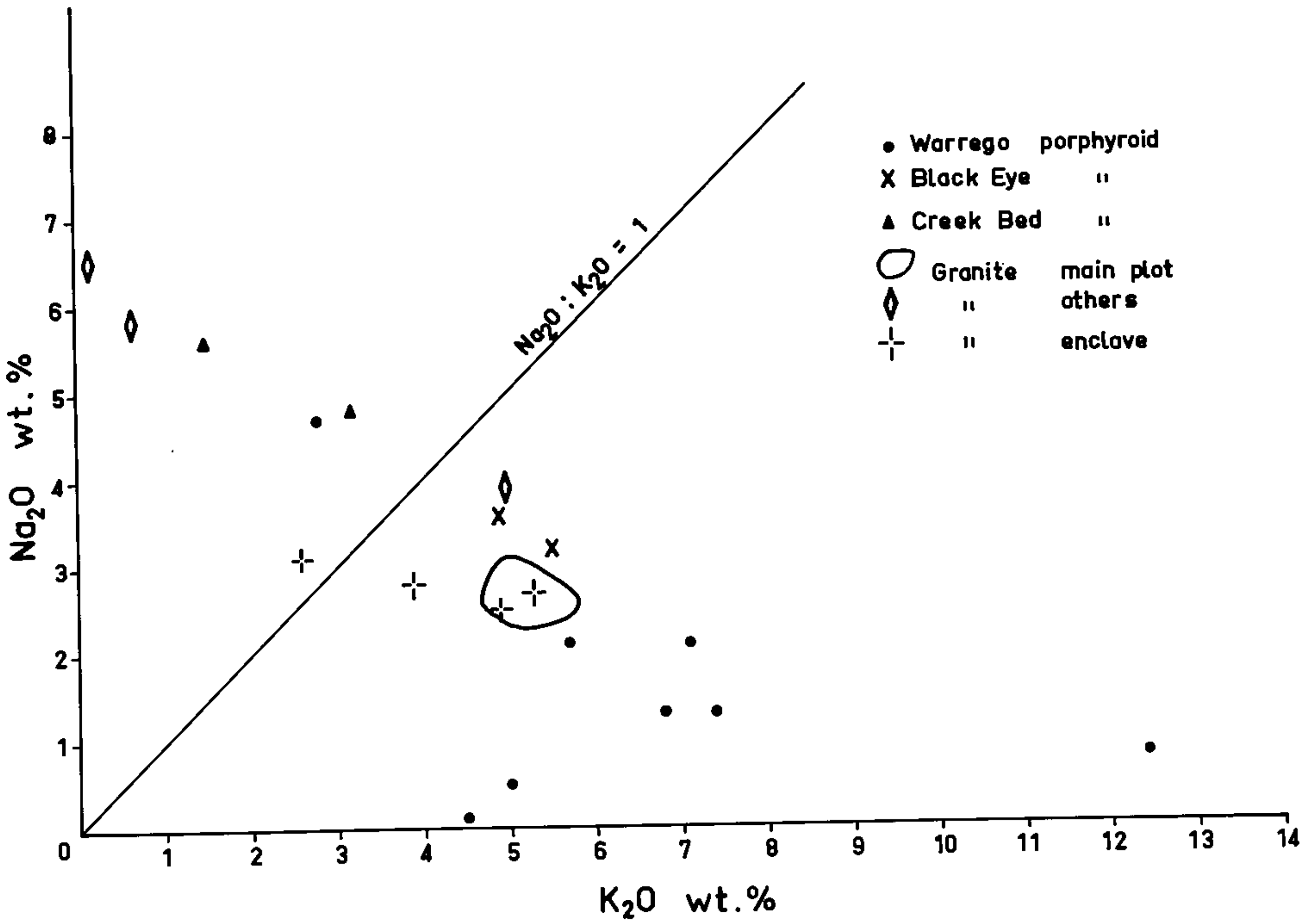
The three Warrego samples comprising group B have either very high values for total alkalies ($K_2O + Na_2O$ equal to 12.3 specimen 249) or very low values ($K_2O + Na_2O$ being 4.57 or 5. and they have the lowest sodium to potassium ratios of any of the other porphyroids (Fig. 16). Specimen 249 also has a hig Al_2O_3 and MgO content and a low SiO_2 content when compared to the other porphyroids.

The quartz-feldspar porphyroids compare very closely in composition with Nockolds' (1954) average for calc-alkaline rhyolites except for the variable alkali ratio and a generall low CaO content (Table 11 (a), columns 1, 2 and 3).

The porphyroidal compositions are matched more readily by the rhyolitic compositions rather than any compositions attri

Figure 16.

Relationship of alkalies in some Tennant Creek rocks.



Warrego porphyroid
Black Eye "
Creek Bed "
Granite main plot
" others
" enclave
$Na_2O : K_2O = 1$
Na_2O wt.%
K_2O wt.%
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14

Table 11.

Some trace elements and selected element ratios in Tennant Creek rocks.

SOME TRACE ELEMENTS AND SELECTED ELEMENT RATIOS FROM TENNANT CREEK ROCKS

	PORPHYROIDS											
	Warrego								Black Eye		Creek Bed	
Specimen	61	51	87	401	35	94	12	249	480	477	600	602
K (%)	6.13	5.89	5.64	4.71	4.15	2.29	3.70	10.26	4.03	4.57	1.25	2.63
Na (%)	0.99	1.55	0.96	1.59	0.39	3.50	0.08	0.56	2.63	2.34	4.18	3.58
Ca (%)	0.18	0.16	0.12	0.14	0.06	0.72	0.04	0.54	0.23	0.11	0.53	0.29
Rb (ppm)	290	263	319	270	222	190	233	534	194	228	57	77
Sr (ppm)	72	74	55	66	37	243	4	30	68	67	138	171
Ba (ppm)	778	816	923	956	1243	950	416	1130	610	814	651	2026
Th (ppm)	-	-	-	-	-	-	-	-	26	27	16	35
U (ppm)	-	-	-	-	-	-	-	-	4	7	7	n.d.
$Na/K.10^2$	16	26	17	34	9.4	153	2.2	5.5	65	51	334	136
K + Na	7.12	7.44	6.60	6.30	4.54	5.79	3.78	10.82	6.66	6.91	5.43	6.21
K/Rb	211	224	177	174	187	121	159	192	208	200	219	342
$Sr/Ca.10^3$	40	46	46	47	62	34	10	5.6	30	61	26	59
$Ba/K.10^3$	13	14	16	20	30	42	11	11	15	18	52	77
Ba/Sr	11	11	17	15	34	3.9	104	38	9.0	12	4.7	12
Ba/Rb	2.7	3.1	2.9	3.5	5.6	5.0	1.8	2.1	3.1	3.6	12	26
Th/U	-	-	-	-	-	-	-	-	6.5	3.9	2.3	*

	GRANITES - STATION HILL											
	Foliated				Others							
Specimen	621	632	G	510/11	524	607	608	617	615	609	619	616
K (%)	4.32	3.98	4.45	4.36	4.29	4.16	4.39	4.21	0.18	0.56	4.75	4.16
Na (%)	2.07	1.94	2.09	2.03	1.75	2.20	1.92	2.06	4.92	4.29	1.92	2.87
Ca (%)	0.79	1.13	0.67	0.69	0.71	0.69	0.34	0.63	1.17	0.89	0.04	0.68
Rb (ppm)	280	238	293	324	292	195	267	214	13	21	393	114
Sr (ppm)	82	89	66	63	79	90	71	93	209	183	549	124
Ba (ppm)	586	894	460	429	645	784	582	704	222	173	132	924
Th (ppm)	29	38	31	27	28	26	23	23	22	11	14	26
U (ppm)	5	3	10	5	9	9	1	n.d.	7	n.d.	14	1
$Na/K.10^2$	48	49	47	47	41	53	44	49	2733	766	40	69
K + Na	6.39	5.92	6.54	6.39	6.04	6.36	6.31	6.27	5.10	4.85	6.67	7.03
K/Rb	154	167	152	135	147	213	164	197	138	267	121	365
$Sr/Ca.10^3$	10	7.9	9.9	9.1	11	13	21	15	18	21	1373	182
$Ba/K.10^3$	14	23	10	9.8	15	19	13	17	123	31	2.8	22
Ba/Sr	7.1	10	7.0	6.8	8.2	8.7	8.2	7.6	1.1	0.9	0.2	7.5
Ba/Rb	2.1	3.8	1.6	1.3	2.2	4.0	2.2	3.3	17	8.2	0.3	8.1
Th/U	5.8	13	3.1	5.4	3.1	2.9	23	*	3.1	*	1.0	26

	GRANITE				METASEDIMENTS								LAMPROPHYRES	
	Enclaves													
Specimen	521	629	511	505	247	246	309	105	116	95	127	431	63	169
K (%)	4.08	4.42	3.25	2.16	3.87	2.46	2.42	4.03	4.53	1.92	3.77	1.57	5.43	5.54
Na (%)	1.87	2.03	2.10	2.32	0.13	0.09	0.26	0.26	0.13	2.03	0.09	0.18	0.55	0.41
Ca (%)	0.66	0.92	1.43	2.00	0.07	0.09	0.06	0.06	0.15	0.19	0.19	0.06	2.87	1.25
Rb (ppm)	236	209	207	151	249	140	150	275	328	153	253	112	294	286
Sr (ppm)	55	70	80	96	4	n.d.	3	18	2	117	27	20	607	136
Ba (ppm)	943	987	678	616	653	310	311	587	751	439	720	856	7021	7836
Th (ppm)	-	-	-	-	13	8	19	17	35	8	11	18	-	-
U (ppm)	-	-	-	-	13	n.d.	10	n.d.	30	4	11	2	-	-
$Na/K.10^2$	46	46	65	107	3.4	3.7	11	6.5	2.9	106	2.4	12	10	7.4
K + Na	5.95	6.45	5.35	4.48	4.00	2.55	2.68	4.29	4.66	3.95	3.86	1.75	5.98	5.95
K/Rb	173	211	157	143	155	176	161	147	138	125	149	140	185	194
$Sr/Ca.10^3$	8.3	7.6	5.6	4.8	5.7	0	5.0	30	1.3	62	14	33	21	11
$Ba/K.10^3$	23	22	21	29	17	13	13	15	17	23	19	55	129	141
Ba/Sr	17	14	8.5	6.4	163	*	104	33	376	3.8	27	43	12	58
Ba/Rb	4.0	4.7	3.3	4.1	2.6	2.2	2.1	2.1	2.3	2.9	2.8	7.6	24	27
Th/U	-	-	-	-	1.0	*	1.9	*	1.2	2.0	1.0	9.0	-	-

Analysed by D. McP. Duncan.

- not determined   n.d. not detected   * very large to sedimentary rocks, a selection of which are listed for comparison in Table 11 (a). In general, shales (columns 6 and 8) have too low a silica content to rate consideration; those that are siliceous (column 7) have alkali and alumina contents which are too low. Greywacke compositions (columns 9 and 11) fall closer to those of the porphyroids but tend to be low in silica or have soda exceeding potash. The closest approach of a sedimentary composition (column 10) to that of the porphyroi appears to be provided by immature glacial argillites (Spry, 1965).

Selected Trace Constituents.

The concentrations of rubidium, strontium and barium for all of the quartz-feldspar porphyroids are recorded in Table 1 along with the thorium and uranium contents of the Black Eye and Creek Bed samples.

The rubidium content of the rocks which ranges from 57 to 534 p.p.m. behaves in the same manner as the potassium cont being highest in the potassium-rich Warrego representatives and lowest in the Creek Bed samples.

The strontium content of 4 to 243 p.p.m. tends to vary in direct proportion to the total amount of sodium plus calcium.

The barium content of all samples falls between 416 and 2,026 p.p.m. The thorium concentration in the Black Eye and Creek Bed rocks varies from 16 to 35 p.p.m., while the uranium content is very low at several p.p.m.

These trace element values are used in conjunction with certain major element concentrations to calculate selected element ratios (listed in Table 11) which are discussed in due course.

CHAPTER 6.

CHEMISTRY OF SOME ASSOCIATED ROCKS.

Chemistry of Phyllitic Rocks.

Major element analyses of several of the regionally metamorphosed volcanic greywackes and ashes occurring in association with the porphyroids at Warrego are featured in Table 12 along with their normative mineralogy expressed, with due regard to the metamorphic grade, in the epinorm form.

The greywackes and ashes have chemical compositions characteristic enough to be readily distinguished from the quartz-feldspar porphyroids and from each other (Tables 10, 11 11(b) and 12).

The greywackes (specimens 309 and 246) have high silica at 69 to 74%, and lower alumina at 11 to 13% and potash at 2 to 3% relative to the ash deposits (specimen 247, 105 and 116) whose corresponding values for these oxides are 60 to 65%, 16 to 20% and 4 to 6% respectively. These features are readily expressed in the epinorms which show a correspondingly greater content of quartz and a lower content of muscovite in the greywackes relative to the ashes; a feature which was confirmed in a qualitative fashion during thin section examination of the rocks.

Of the trace elements (Table 11), both the barium and rubidium contents reflect proportionately the amount of potash present in the rocks, and hence, the values are larger in the

Table 11 (a)

Average compositions of quartz-feldspar porphyroids, volcanic greywackes and ashes compared with the compositions of some sedimentary rocks.

TABLE 11 (a)

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	73.30	72.58	73.66	72.06	63.11	58.10	73.71	37.87	64.2	66.87	73.04
Al_2O_3	12.93	13.46	13.45	11.89	17.81	15.41	7.25	14.23	14.1	15.36	10.17
Fe_2O_3	0.58	1.23	1.25	1.20	3.01	4.02	2.63	2.97	1.0	2.81	0.56
FeO	2.16	1.69	0.75	5.61	3.64	2.45	0.44	1.63	4.2	1.89	4.15
MgO	1.06	0.67	0.32	1.54	2.39	2.44	1.47	3.29	2.9	2.40	1.43
CaO	0.21	0.24	1.13	0.11	0.13	3.11	1.72	14.73	3.5	0.34	1.49
Na_2O	1.94	3.35	2.99	0.24	0.23	1.30	1.19	0.43	3.4	1.21	3.56
K_2O	6.74	5.17	5.35	2.94	4.99	3.24	1.00	5.96	2.0	6.60	1.37
Ign.loss	1.37	1.04	-	3.22	3.45	-	-	-	-	-	-
H_2O^+	-	-	0.78	-	-	5.00	6.94	2.67	2.1	1.35	2.36

1. Warrego Porphyroid (Group A - average of 4 analyses).
2. Black Eye Porphyroid (average of 2 analyses).
3. Average of 22 calc-alkali rhyolites and rhyolite-obsidians, Nockolds (1954).
4. Metamorphosed volcanic greywacke (average of 2 analyses), Warrego area.
5. Metamorphosed volcanic ash (average of 3 analyses), Warrego area.
6. Average shale (Clarke, 1924).*
7. Siliceous shale (Hoots, 1938).*
8. Potassic shale (Schmitt, 1924).*
9. Average greywacke (Pettijohn, 1949).
10. Glacial argillite (Pettijohn, 1949).*
11. Greywacke sandstone (Eigerfeld, 1933).*

* Taken from Spry (1965).

Table 11 (b)

Quartz-feldspar porphyroids, volcanic greywackes and ashes compared with some sedimentary rocks with respect to SiO_2, Al_2O_3, K_2O, Na_2O and CaO.

TABLE 11 (b)

$K_2O > Na_2O$

	SiO_2	Al_2O_3	K_2O	CaO
volcanic ashes (Warrego)	60-65	16-20	4-6	0.10-0.20
volcanic greywackes (Warrego)	69-74	11-13	2-3	0.10
quartz-feldspar porphyroids (Warrego-Group A-and Black Eye).	72-74	12-14	4-8	0.15-0.30
† average shale	58	15	3	3
† potassic shale	38	14	6	15
† glacial argillite	67	15	7	0.3

$Na_2O > K_2O$

	SiO_2	Al_2O_3	K_2O	CaO
† average greywacke	64	14	2	3.5
† greywacke sandstone	73	10	1	1.5
† siliceous shale	74	7	1	2

† taken from Table 11 (a)

ANALYSES AND MOLECULAR NORMS OF TENNANT CREEK ROCKS

	Granite enclaves					Warrego metasediments						Inset B sediments	
Specimen	521	629	511	505		309	246	247	105	116	95	127	431
SiO_2	74.28	70.79	70.40	68.20		74.33	69.82	64.35	64.27	60.72	78.20	69.35	83.20
TiO_2	0.48	0.56	0.72	0.81		0.57	0.53	0.57	0.56	0.71	0.42	0.45	0.56
Al_2O_3	12.44	13.71	13.64	14.21		11.07	12.72	17.05	16.68	19.71	10.84	14.28	7.22
Fe_2O_3	2.55	3.67	4.72	6.21		2.37	0.04	2.54	4.80	1.70	0.86	3.57	3.23
FeO	-	-	-	-		3.35	7.88	4.87	3.17	2.88	1.73	0.96	0.00
MnO	0.05	0.04	0.05	0.07		0.07	0.07	0.06	0.05	0.09	0.06	0.03	0.02
MgO	0.42	0.42	0.11	1.46		1.42	1.66	1.84	1.75	3.59	0.98	0.77	0.28
CaO	0.92	1.29	2.00	2.80		0.09	0.13	0.10	0.09	0.21	0.26	0.27	0.08
Na_2O	2.52	2.73	2.83	3.12		0.35	0.12	0.17	0.35	0.18	2.74	0.12	0.24
K_2O	4.91	5.33	3.92	2.60		2.91	2.96	4.66	4.86	5.46	2.31	4.54	1.89
P_2O_5	0.04	0.03	0.14	0.15		0.03	0.09	0.06	0.13	0.21	0.09	0.06	0.03
Ign. loss	0.48	0.45	0.59	0.82		2.95	3.50	3.53	2.97	3.97	1.05	3.46	2.04
H_2O^-	0.05	0.05	0.05	0.04		0.07	0.06	0.07	0.08	0.13	0.12	0.72	0.65
Total	99.14	99.07	99.17	100.49		99.58	99.58	99.87	99.76	99.56	99.66	98.58	99.44
	Mesonorms*					Epinorms							
Q	37.46	30.48	33.88	32.87	Q	59.81	54.17	42.70	41.94	34.98	51.31*		
Or	25.38	26.48	17.25	3.86	Or	6.32	13.42	8.97	6.72	11.50	9.50		
Ab	23.50	25.40	26.50	28.85	Ab	3.40	1.20	1.65	3.40	1.75	25.65		
An	4.40	6.50	9.35	13.30	Zo	0.19	0.05	0.13	0.00	0.00	0.75		
C	1.61	1.29	1.66	1.71	Ms	17.40	8.02	29.02	33.85	31.99	4.06		
bi	7.54	9.78	11.04	19.10	chl	9.25	22.08	13.68	7.65	16.43	7.60		
mt	-	-	-	-	mt	2.70	0.04	2.87	5.40	1.89	0.93		
ap	0.11	0.05	0.32	0.32	il	0.86	0.82	0.86	0.84	1.06	0.19		
					ap	0.08	0.21	0.13	0.16	0.35			
ΣQ+Or+Ab	86.34	82.36	77.63	65.58		69.53	68.79	53.32	52.06	48.23	86.46		

ashes (587 to 751 p.p.m. and 249 to 328 p.p.m.) when compared to the greywackes (310 and 311 p.p.m. and 140 and 150 p.p.m. respectively). The strontium, thorium and uranium concentrati are all low, with no obvious pattern throughout the rock types

Relative to the quartz-feldspar porphyroids, (Group A), the greywackes have fairly similar SiO_2 and Al_2O_3 but low K_2O contents, while the ash deposits have low SiO_2, generally similar K_2O (when compared with the Black Eye samples) and hig Al_2O_3 contents (Table 11.(b)). Both the greywackes and ashes are characterized by low Na_2O and high total iron plus MgO contents with respect to the quartz-feldspar porphyroids (Group A). A low CaO content (i.e. most are less than 0.3%) is typical of all of the rock types - greywacke, ash and porphyroid.

The volcanic greywackes are distinct from most greywackes in having K_2O greater than Na_2O and very low CaO contents (Table 11(b)) except for the argillite compositions (Tables 11(a) and 11(b)) from which they differ in having low Al_2O_3 and K_2O contents.

Specimen 95, which is texturally intermediate between an ash and a greywacke, is worthy of note as it contains a relatively high soda content of over 2% caused by a substantia amount of albite in the rock. Strontium is also relatively high at 117 p.p.m.

Two fragmental rocks analysed from the Inset B area are specimen 431, a volcanic greywacke, and specimen 127, a siltsto (possibly in part tuffaceous). Both of the analyses show only vague similarities to the compositions of the greywackes and a deposits respectively of the Warrego area.

Chemistry of Lamprophyres.

Most of the lamprophyres are altered to assemblages of chlorite, white mica and quartz with obliteration of their original texture to form an irregular, granoblastic fabric.

Comparison of the chemistry of a relatively fresh lamprophyre (specimen 63, Table 14) with the average analyses of different lamprophyre varieties listed by Joplin (1966) confirms that the former rock shows greatest similarity to the minette composition. Relative to that average composition (see Table 14), specimen 63 has higher SiO_2, MgO and K_2O, lowe Al_2O_3, CaO and Na_2O and a similar total iron content.

A low to medium silica content associated with substantia amounts of Ca, Mg and total iron and relatively high alkalies is typical of the chemistry of lamprophyres with potassium being much greater than sodium only in the minettes.

These chemical characteristics are still preserved in the altered lamprophyres (specimens 169 and 237, Table 14).

High barium contents, suggested by Joplin (1966) to be typical of the more silica-rich lamprophyres, are characteristi of both the fresh and altered rocks and range from 0.5 to 0.9 wt. % BaO (Table 14).

TABLE 14.

Composition of Lamprophyres.

Specimen	63	169	237		M
SiO_2	53.34	58.70	52.30		51.17
TiO_2	1.41	1.43	1.05		1.36
Al_2O_3	11.70	12.12	11.32		13.87
Fe_2O_3	2.99	5.64	3.27		3.27
FeO	4.55	2.43	6.18		4.16
MnO	0.23	0.18	0.20		-
MgO	10.18	6.86	11.81		6.91
CaO	4.01	1.75	2.79		6.58
Na_2O	0.74	0.55	0.55		2.12
K_2O	6.54	6.67	4.56		5.49
P_2O_5	1.36	1.37	1.21	CO_2	1.30
BaO	0.78	0.87	0.51	H_2O+	2.42
Ign.loss	2.14	1.94	5.24		
H_2O^-	0.62	0.38	0.25		
TOTAL	100.59	100.89	101.24		
Sr (p.p.m.)	607	136	-		
Rb (p.p.m.)	294	286	-		

Analysed by D. McP. Duncan.

Ferrous iron determined by Miss S. Hill.

M - average composition of 64 minettes from Joplin (1966).

TABLE 14 (a)

Redistribution of K, Na and Ca in porphyroids.

Specimens	Postulated changes in system
GROUP A	
Warrego 51, 61, 87, 401	K in, Na out
Black Eye 480, 477	May have original alkali ratios
Warrego 94 Creek Bed 600, 602	Na in, K out
GROUP B	
Warrego 12, 35	Na out
Warrego 249	K (Mg) in
All specimens	Ca out

CHAPTER 7.

THE STATION HILL GRANITE.

PREVIOUS WORK.

In the Tennant Creek area, two granite masses situated in the Warramunga Group rocks are the Tennant Creek Complex and the Cabbage Gum Complex lying to the north and south respectively of the town of Tennant Creek.

The main areas of exposure of the northern granite mass are centred around Station Hill and White Hill lying to the west and east respectively of the Stuart Highway. Estimates of the size of this mass by Crohn and Oldershaw (1965) and Whittle (1966) suggest that it may be 15 - 20 miles long by 6 miles wide, elongated in an east-west direction and occupying a dome-like structure with the sediments dipping radially off the granite. The contacts with the country rocks, where visible, are sharp and roughly parallel to the strike of the sedimentary bedding which is transgressed by the granite locally.

The Tennant Creek Complex has been divided by Crohn and Oldershaw (1965) into four phases in the Station Hill area. The three most important are -

A) main, "porphyritic" granite, foliated in places,

B) coarse-grained granite, and

C) fine-to medium-grained granite.

These members are referred to collectively in this investigati as the Station Hill Granite.

In the Station Hill area, the "porphyritic" granite occupies about 60% of the available outcrop, while the fine-to medium-grained granite occurs mainly along the south-west marg and is also present as dykes intruding the other phases of the complex. The coarse-grained granite appears as several small bodies in the north-east of this area (see sketch map, Fig.17)

The contacts of the phases are smooth, sharp and sometime chilled which indicates that the members have an intrusive nature (Plate 20c), the order of introduction being as listed above.

Xenoliths.

Xenoliths are locally important, attaining up to 30% by volume of the first phase "porphyritic" granite and are common along the north-east outcrop margin in the Station Hill area.

Contact metamorphism.

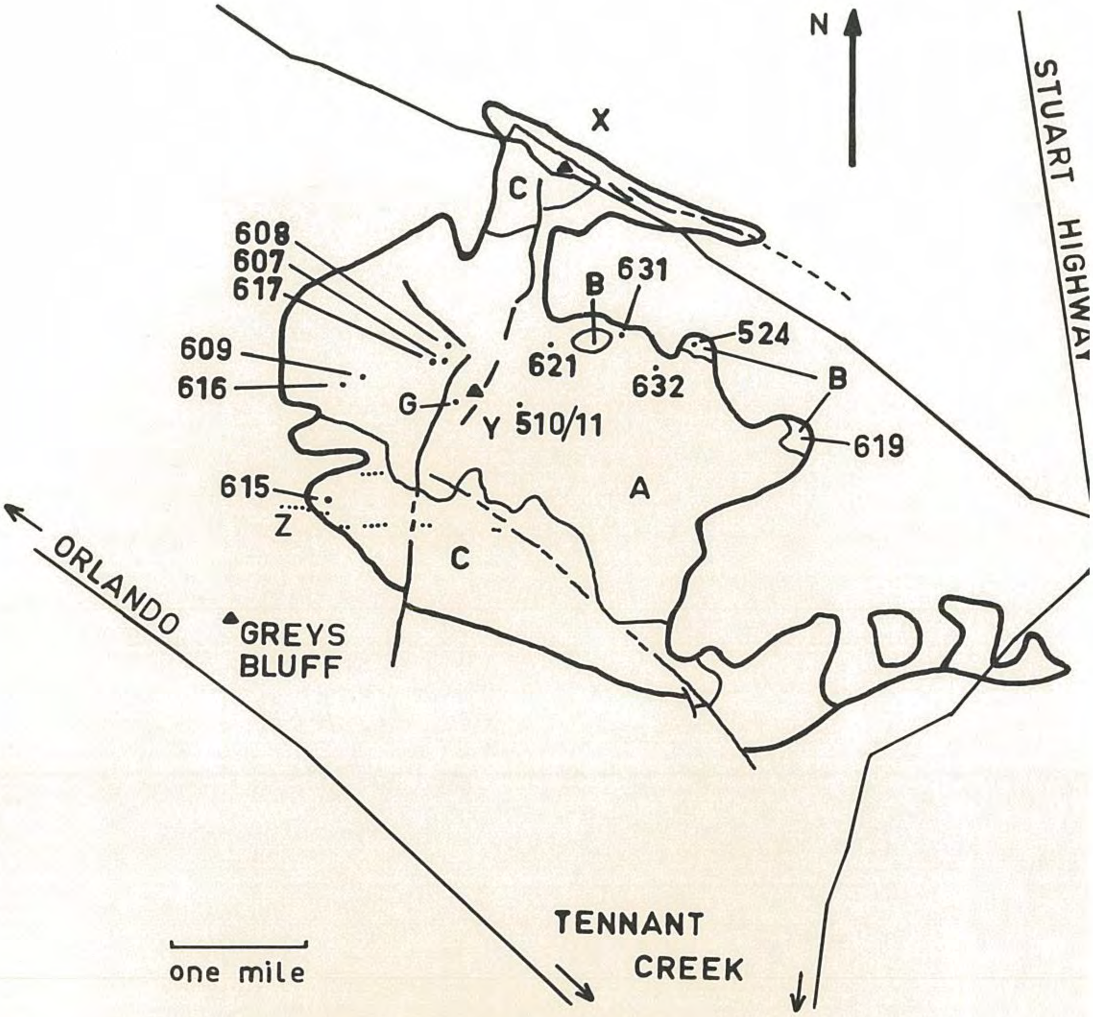
In the relatively well-exposed country rocks to the south reported by Crohn and Oldershaw (1965) to be mostly fine-grain siltstones and shales, the granite complex has produced a broa contact aureole. Within the aureole, the country rocks are baked and recrystallized with the appearance of spotted biotit hornfelses.

Foliation.

Most rocks in the complex are sheared to some degree and zones of strong foliation with gneissose fabrics are apparent

Figure 17.

Sketch map of the Tennant Creek Granite Complex (along with the locality of specimens used in this investigation) in the Station Hill area based on the B.M.R. Map Sheet 238. (Crohn and Oldershaw, 1965).



STATION HILL GRANITE - - - SPECIMEN LOCALITIES

PHASES A - porphyritic ▲ X - QUARTZ HILL

B - coarse - grained ▲ Y - STATION HILL

C - fine - grained

...... QUARTZ - FELDSPAR PORPHYROID

Z - CREEK BED PORPHYROID

based on B.M.R. Sheet 238.

within the "porphyritic" granite. The foliation is sub-vertical in attitude and generally strikes east-west, parallel to the regional cleavage and shearing in the country rocks.

Age.

The age of the granitic rocks was originally determined b Hurley et. al. (1961) by radioactive age dating as 1,630 milli years based on the measurement of a gneissose granodiorite fro the Cabbage Gum Complex using the K-Ar method. This was regarded by Walpole and Smith (1961) to be a Lower Proterozoic age.

More recently, however, according to Whittle (1966), a revised dating by the Rb-Sr method (Leggo, Walpole and Compsto in prep.) indicates that the granite age lies in the range 1,700 to 1,800 million years. The granites may then occur at the base of the Middle Proterozoic referring to the time scale accepted by Walpole, Roberts and Forman (1965) of 1,400 - 1,80 million years for that division.

In terms of a sequence of three phases of deformation proposed for the Mount Woodcock area (immediately to the north by Dunnet and Harding (1965), the granitic rocks are considered by them to have been intruded synchronously with, or slightly later than, the first deformation phase and were later variably foliated by the second phase which was responsi for the penetrative, sub-vertical, east-west trending regional cleavage.

PRESENT INVESTIGATION.

The Petrography, Mineralogy and Chemistry of the Station Hill Granites.

The "Porphyritic" Granite (phase A).

PETROGRAPHY.

The phase A granite is a coarse-grained, grey to pink rock with a foliation which becomes intense in zones throughou the body.

In its most massive aspect (e.g. specimen 632, Plate 20t 21a) the rock consists of prominent grey megacrysts of potassium feldspar up to 2 cms. across set in a coarse-grained slightly foliate groundmass composed of pale blue to glassy, spotted quartz up to 10 mms. in size, white to transparent plagioclase reaching 5 mms. and black, irregular patches of biotite and minor potassium feldspar.

The texture of the groundmass is dominated by the discret subhedral grains of plagioclase and elliptical, anhedral quart grains forming a framework open in some places and closed in others (Plate 21a). The remainder of the groundmass is made u of biotite-rich aggregates with associated irregular quartz and subhedral plagioclase grains (approx. 0.4 mms. across).

The foliation is produced by a crude parallelism of elong quartz grains and irregular biotite wisps (Plate 21b and c). The potassium feldspar megacrysts tend to be oriented with the

Plate 20 (a) - main, phase A granite in Station Hill area.

Granites in the Station Hill area.

Plate 20 (b) - fabric of main, phase A granite in Station Hill area.

Plate 20 (c) - contact between main, phase A granite and phase B granite, Station Hill area.

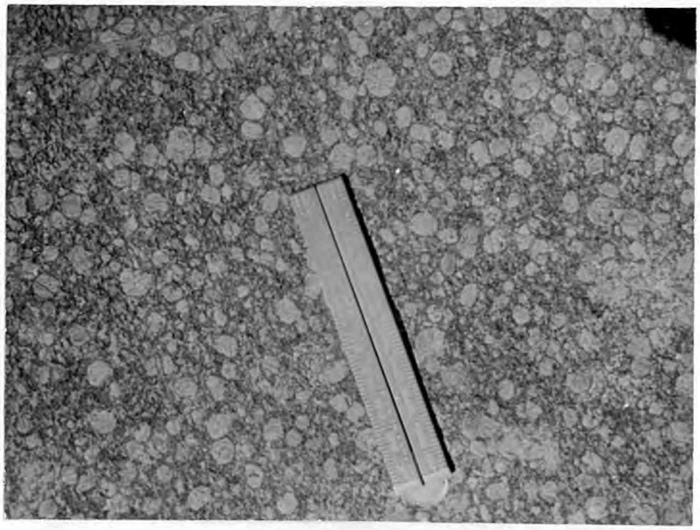


Plate 21 (a) - massive aspect.

(ruler graduated in 1/2 inches)

Fabric of main, phase A Station Hill granite.

Plate 21 (b) - foliated aspect.

(as above)

Plate 21 (c) - thin section detail of foliated fabric (height of field - one inch; crossed polars)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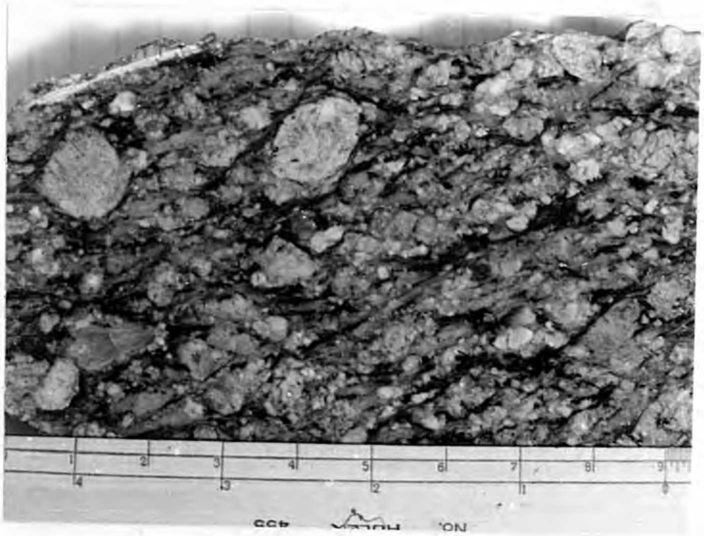


longer dimensions in the foliation surface. As the surface becomes more strongly expressed, the potassium feldspar megacrysts give way to irregular strings of that mineral derived from granulated megacrysts (e.g. specimen 621, G) until the latter are almost entirely suppressed, conferring on the rock (e.g. specimen 510/11) a relatively even-grained, foliated appearance.

In summary, relative to the least foliated granite, the more gneissic samples show an increase in the

1) granulation of potassium feldspar megacrysts,
2) alteration of plagioclase to white mica and epidote,
3) shearing and recrystallization of quartz,
4) amount of biotite altering to chlorite, sphene and opaque minerals,
5) amount of white mica contributing to the foliation, a
6) development of incipient, myrmekitic rims around potassium feldspar.

Classification.

Classification of the foliated "porphyritic" granite on a mineralogical basis according to the relative proportions of quartz, potassium feldspar and plagioclase proves to be diffic as a result of the wide range in grain size both among the different minerals and within a single mineral species due in part to granulation of megacrysts.

The approximate modal proportions obtained for the specim suggest that the rocks be termed calc-alkali granites (s.s.) in Nockolds' (1954) classification. They also plot (Fig.1, Appendix I) in the granite (s.s.) sub-field 3(a) of Streckeiser (1967) in which, among a few others, granites of the rapakivi type commonly occur. However, comparison of the modes with the calculated mesonorms of the rocks indicates that the plagioclase and quartz values of the former are considerably lower relative to the potassium feldspar value than they should be according to the latter. Hence the true mineral proportion may actually be that of an adamellite (Nockolds, 1954), or plot in the more common granite (s.s.) sub-field 3(b) of Streckeisen.

MINERALOGY.

1. POTASSIUM FELDSPAR.

Thirteen potassium feldspar megacrysts of the "porphyritic granite were investigated in the same manner as those in the quartz-feldspar porphyroids.

<u>Texture</u>.

1) Morphology and size.

The large megacrysts of potassium feldspar occurring in the "porphyritic" granite are generally greater than 1 cm. in diameter ranging up to 2½ cms. and as such appear similar to those present in the quartz-feldspar porphyroids. Both equant and elongate grains are found, the latter approaching as before a length to width ratio of 2 : 1. Grains with cross-sections showing an approach to tabular, elliptical and circular outline are present (Plates 22 and 23).

Plate 22 (a)

(width of field - one inch; crossed polars)

Potassium feldspar megacrysts in the main, phase A Station Hill granite.

Plate 22 (b)

(as above)

Plate 22 (c)

(as above)

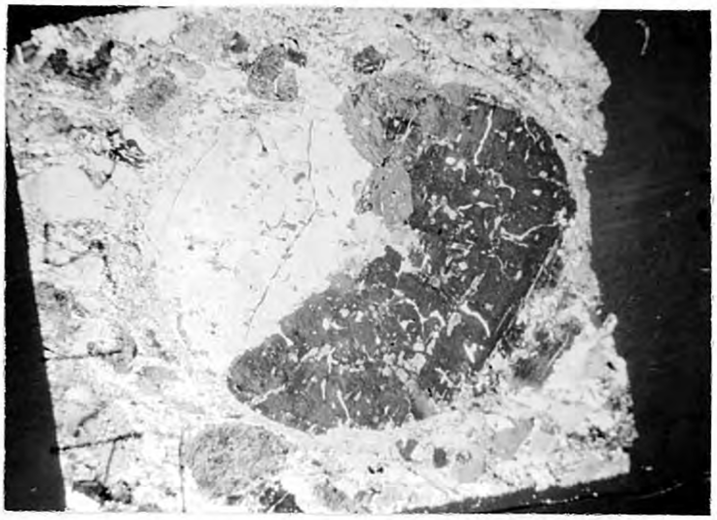


Plate 23 (a)

(height of field - one inch; polarised light)

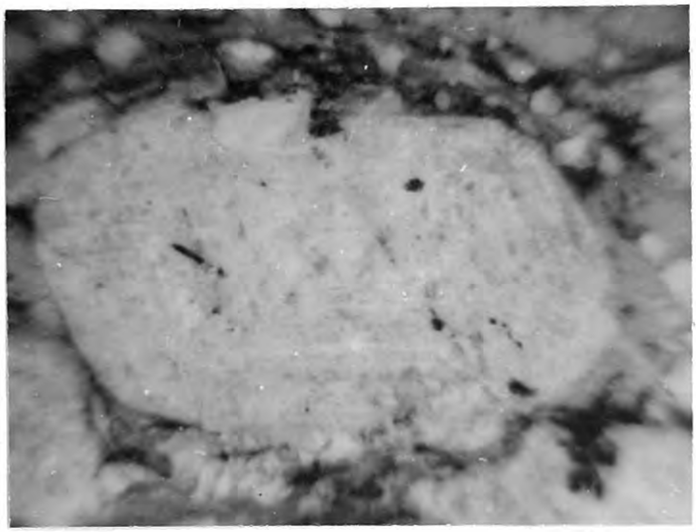
Potassium feldspar megacrysts in the main, phase A Station Hill granite.

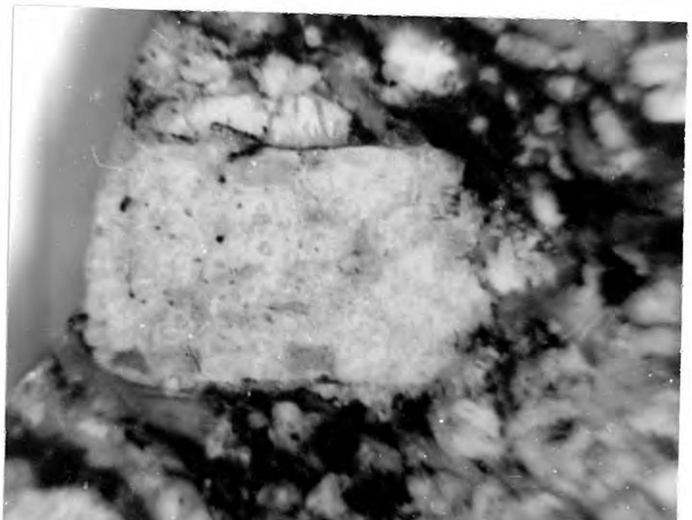
Plate 23 (b)

(height of field - one inch)

Plate 23 (c)

(height of field - one inch)





In contrast to the substantial proportion present in the Warrego and Black Eye Porphyroids, there is a characteristic absence of fractured grains of potassium feldspar in the massi little-deformed granite fabrics and the grain perimeters are made up of combinations of approximately straight and curved edges.

2) Inclusions.

In hand specimen, the grains of potassium feldspar appear to possess relatively few inclusions and there are no obvious inclusion-filled embayments or cavities similar in nature to th in the porphyroidal potassium feldspars. However, thin sectio examination reveals a variety of different inclusions -

a) Vermicular quartz inclusions.

Microscopically, the megacrysts can be seen to contain numerous vermicular inclusions, often discontinuous, and being comprised almost exclusively of quartz, which may or may not be in optical continuity with adjacent inclusions. In their sinuous appearance, these inclusions are reminiscent of the infilled embayments of the potassium feldspar grains in the porphyroids. They occur both in the core of the megacrysts and and running in from the perimeters (Plates 22b and 23a). In places, they exhibit a tendency for preferred orientation along cleavage directions (Plate 24c) and tend to follow the twin interfaces of composite grains (Plate 24b).

In detail, the edges of the inclusions are often intricate

Plate 24 (a)

(width of field - 2 mms; crossed polars)

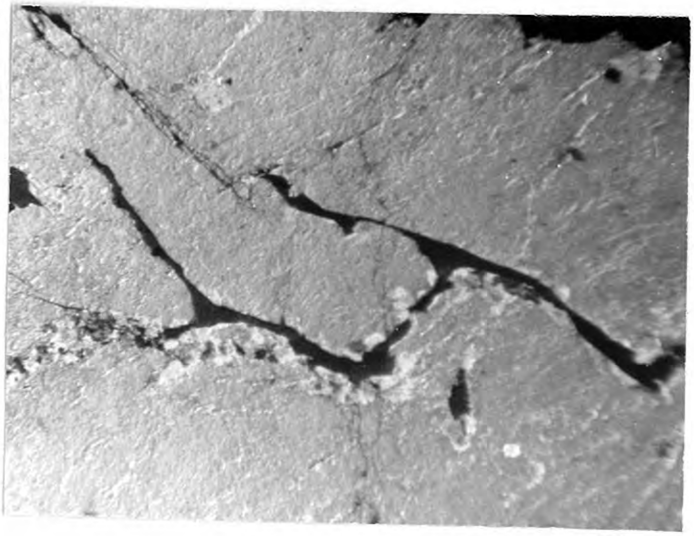
Detail of quartz vermicules in potassium feldspar megacrysts of the main, phase A Station Hill granite.

Plate 24 (b)

(as above)

Plate 24 (c)

(as above)



and show outlines made up of combinations of cusps which tend to be convex towards the inclusions (Plate 24a and b).

b) Small plagioclase inclusions.

These inclusions are ubiquitous in the potassium feldspar of the granite. The plagioclase may take the form of small laths (less than 0.5 mm.) but often is more irregular having runiform shapes (Plate 25a). Where the inclusions are plentif they may be grouped into one or two concentric zones, the outer one sometimes being associated with, and on occasions indistinguishable from, an intermittent plagioclase mantle. Some zones are ill-defined, others fairly distinct and where the latter cross the interface of twinned grains they are undeviated. The plagioclase, although generally altered, shows slight continuous, normal compositional zoning.

c) Large plagioclase inclusions.

Occurring as fairly well-shaped laths (2-3 mms. long), th scarce inclusions are oriented with their larger dimensions parallel to a cleavage or the nearest crystal edge of the hos feldspar (Plate 23c). Alteration to white mica or epidote obscures the plagioclase.

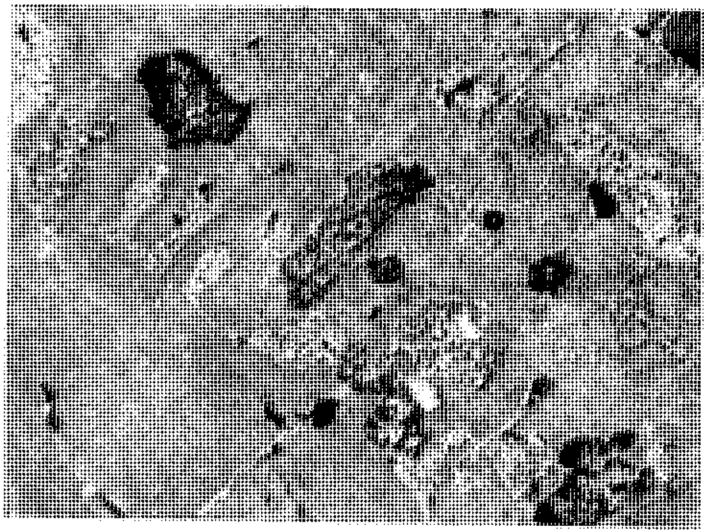
d) Other inclusions.

Biotite, chlorite, tourmaline, epidote and opaque mineral are occasionally recorded. Quartz screens wholly or partially surround the plagioclase and other inclusions.

Plate 25 (a) - runic plagioclase inclusions in potassium feldspar of the main, phase A Station Hill granite (width of field - 2 mms; crossed polars).

Plagioclase textures in main, phase A Station Hill granite.

Plate 25 (b) - plagioclase with synneusis texture in main, phase A Station Hill granite (width of field - 3 mms; crossed polars).



3) Plagioclase Mantles.

Plagioclase mantles are by no means ubiquitous and only occur around certain grains of potassium feldspar where they show thin (less than 0.5 mm.), discontinuous development. The inner edges of the mantles against the host feldspar are typically irregular, while the outer boundary is relatively smooth and well-defined.

4) Euhedral Zoning.

Traces of faint zoning are detectable in hand specimens of some potassium feldspars (Plate 23b). The zoning is euhedr in character and is parallel to regular crystal edges.

5) Twinning.

Cross-hatched twinning is common throughout the potassium feldspars of the granite and is slightly coarser than that occurring in the potassium feldspars of the porphyroids.

Composite grains, usually of two sub-individuals, occur and on measurement with the universal stage, prove to be Carlsbad twins (Table VIII, Appendix II). The twins are inter-penetrant with very irregular composition surfaces and show little evidence of re-entrant angles (Plate 22).

Optical determination.

The techniques employed to investigate the optical parameters of the potassium feldspars from the porphyroids (Chapte were repeated on thirteen potassium feldspar megacrysts from th "porphyritic" granite.

The optic axial angles, 2Vx, were found to be between 70° and 90° (Table 3 and Fig. 5) and to show a significant variati within individual grains (i.e. a variation greater than the precisi of the method ± 2°).

With respect to optical orientation, the potassium feldspars have triclinic symmetry, the optic axial plane lying approximately perpendicular to (010).

The refractive index, Nx, is similar to the values of 1.520 to 1.522 obtained for the porphyroidal potassium feldspa (Table IX, Appendix II).

X-ray determination.

The obliquities of the potassium feldspar grains measured as in Appendix II are 0.85 to 0.96 (Table 3 and Fig.5) and are those of near-maximum microcline.

The variation of obliquity among potassium feldspar grain within single hand specimens appears to be small (i.e. 0.06) judging from measurements on ten megacrysts in specimen, 626 (Table X, Appendix II).

Composition.

The individual compositions of the thirteen megacrysts of potassium feldspar selected from six specimens of the "porphyritic" granite were determined, using the $\bar{2}01$ X-ray diffraction method (described in Appendix II).

The potassium feldspar is microperthitic, the plagioclase occurring mainly as thin (0.01 mms.), discontinuous films with fairly constant orientation and distribution. The averag amount of plagioclase in perthitic intergrowth, deduced from t increase of plagioclase in solid solution within the host potassium feldspar after heat treatment (Appendix II), proves to be 10 mol. % (the range in values being 12 to 28 mol. %). During hand picking of the potassium feldspar, an attempt was made to exclude mantle plagioclase and any large plagioclase inclusions.

The potassium feldspar averaging approximately 80% by volume of the megacrysts has up to $6\frac{1}{2}$ mol. % Ab + An in solid solution, which increases on heating to an average value of 22 mol. % Ab + An (the range being 16 to 29 mol. %, Table 3). Small variations in bulk composition (i.e. greater than the $\pm$ 1 mol precision of the method) are recorded among grains within some of the hand specimens. The average bulk composition of all potassium feldspar megacrysts from the "porphyritic" granite measured by the X-ray diffraction method is in close agreement with that of the potassium feldspar separated from four specimens, purified (Appendix V), and fully analysed using X-ray fluorescence techniques (Table XI, Appendix II).

In mol. %, albite, the individual potassium feldspar separates show little variation being between 19.1 and 22.3% (Table 4). The mol. % anorthite content ranges from 0.9 to 1.4%.

The contents of rubidium, strontium and barium are 348 to 560 p.p.m., 69 to 133 p.p.m. and 2,743 to 4,076 p.p.m. respectively.

2. PLAGIOCLASE.

Texture.

Plagioclase feldspar is present in the granite as white, grey or light green subhedral grains ranging up to 5 mms. in size.

Under the microscope, much of the unaltered plagioclase contained in the least foliated granite (e.g. specimen 632) is seen to possess numerous delicate oscillatory zones. Twinning is also fairly common being either simple or lamellar in style and using criteria proposed by Vance (1961), both primary and secondary twins can be identified.

Some of the grains are obviously composite in the sense that each is composed of several individuals whose concentric zoning illustrates that at some stage in the formation of the grain, the individuals in question coalesced. Subsequently, later zones grew around the composite nucleus (Fig.18a, Plate 25b). The contact surfaces are generally irregular, but some may be approximately straight (Fig. 18b).

Optical and X-ray determination.

Measurements on the attitude of the optical indicatrix in the plagioclase performed according to the method of Rittmann a

Figure 18.

Diagrammatic sketches of textures in plagioclase from granitic rocks at Tennant Creek.

Largest grain dimension :-

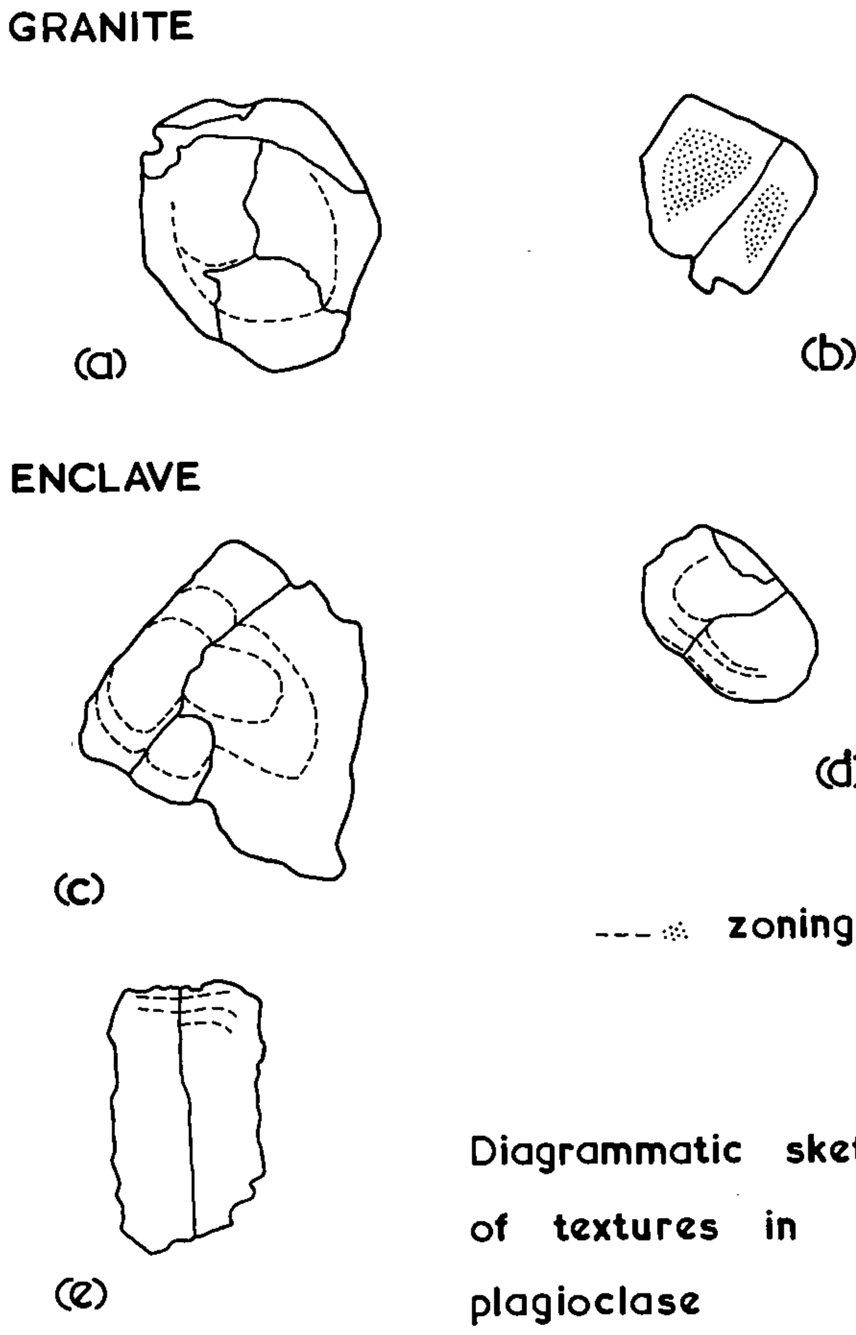
a) 3 mms. (specimen 632).

b) 2 mms. (specimen 632).

c) 3 mms. (specimen 519).

d) 2 mms. (specimen 625).

e) 3 mms. (specimen 625).



Diagrammatic sketches of textures in plagioclase

El-Hinnawi, 1961 (Appendix III), demonstrate that the plagioclases are in a high-order structural condition and also give the composition of the plagioclase. The structural state is confirmed by the values for the optic axial angle, 2Vx, and th separation of selected X-ray peaks (Table 15).

Composition.

Plagioclase compositions were determined optically as mentioned above and are listed in Table 15. In the relatively undeformed rocks (e.g. specimens 632 and 626), the plagioclase grains are andesine and many possess narrow rims of oligoclase The andesine cores commonly show delicate, concentric oscillat zoning never greater than a range of 4% An. As the granite becomes more foliated, the cores become masked by epidote and white mica as the plagioclase decalcifies to oligoclase (speci men G) or albite (specimen 621).

The inclusions of plagioclase in the potassium feldspar megacrysts prove to be andesine with oligoclase or albite rims sometimes myrmekitic. The incipient plagioclase rims around the potassium feldspar megacrysts consist of andesine or oligo clase with slight normal zoning. Much of the rim and inclusio plagioclase is altering to epidote and white mica.

The plagioclase was not analysed for major elements but barium and strontium contents measured by emission spectrograp (Appendix IX) range from 230 to 370 p.p.m. and 150 to 190 p.p. respectively (Tables 7 and 8).

TABLE 15.

Optical and X-ray data on plagioclase from the "porphyritic" Station Hill Granite.

Specimen	$2Vx^{o}$	X-ray peak separation 131-1$\bar{3}$1	$\bar{1}$32-131	Composition by optics		Normati[ve] value
632	100	1.65	2.45	An_{35}	M	An_{25}
	98	-	-	An_{39-37}	M	
	-	-	-	$An_{37,27}$	M	
	-	-	-	$An_{38,21}$	M	
510/11	92	1.35	2.60	$An_{30,9}$	M	An_{15}
	-	-	-	$An_{37,13}$	M	
G	88	1.18	2.68	An_{22}	M	An_{16}
	-	-	-	An_{8}	M	
621	-	1.20	2.71	albite	M	An_{16}
626	98	-	-	$An_{36,16}$	M	
	97	-	-	An_{39-20}	M	
	96	-	-	$An_{36,16}$	I in LM	
	-	-	-	An_{15-9}	I in LM	
	-	-	-	An_{31}	I in LM	
	-	-	-	$An_{40,23}$	I in LM	
	-	-	-	$An_{40-32,21}$	I in LM	
	-	-	-	An_{28-17}	R	
	-	-	-	An_{30}	R	

M- individual grains, I in LM- inclusions in potassium feldsp[ar] grains, R- rims of potassium feldspar grains.

3. QUARTZ.

The pale blue quartz grains reaching up to 10 mms. in siz are characteristically elliptical in section in the relatively undeformed fabrics. The spotted nature of the grains is due t embayments and internal cavities containing feldspar and occasional biotite flakes. Microscopically, the quartz is see to be strained and recrystallized to mosaics of quartz granule among which the embayments are still recognisable.

4. BIOTITE.

Biotite, with a pleochroism scheme- X-straw yellow; Y, Z-dark brown- and its alteration products such as chlorite, sphene and opaque minerals constitute the main ferromagnesian constituents.

Apatite and zircon occur in accessory amount.

Other Granites (phases B and C).

Along with samples of the main "porphyritic" granite (phase A), specimens were collected of the other subsidiary members of the Tennant Creek Granite Complex in the Station Hil area. The purpose of this was to compare the petrography, mineralogy and composition of the minor phases of the complex with the main member and also with the quartz-feldspar porphyroids.

The main features of the petrography and mineralogy of th granites (sensu lato, as no modal analyses were performed on t rocks) are presented in Table 16. They show a variety of aspe

Table 16.

Petrographical and mineralogical summaries of subsidiary granite phases in the Station Hill area.

GRANITES - OTHER PHASES IN STATION HILL AREA

Specimen	General Description	Potassium feldspar $2Vx^o$	Potassium feldspar Δ	Plagioclase $2Vx^o$	Plagioclase Composition by optics	Plagioclase Normative Value	Micrographic intergrowth	Mafics and accessories	Occurrence (see locality map)
524	Overall pink, massive, medium-grained, slightly porphyritic	-	0.88	96	An_{37-31}	An_{16}	minor	Biotite, chlorite epidote, opaques	Several small masses in the north-east of the area Phase (B)
608	Red, massive, coarse-grained, porphyritic	-	0.94	obscured		An_5	none	Chlorite, epidote	Occupying the area to the west of Station Hill - may be red, massive variants of phase (A) but could be a separate member
607	Red, massive, medium-grained, slightly porphyritic	-	-	obscured		An_{13}	minor	Chlorite, epidote, sphene, opaques	
617	Red, massive, medium-grained, non-porphyritic	-	-	obscured		An_{12}	minor	Biotite, chlorite, epidote, sphene, opaques	
619	Neutral, massive, fine-grained, porphyritic	77-83	0.88	88	An_{21}	An_0	common	Biotite	Small body in north-east corner of area, phase (C)?
616	Overall pink, massive, medium-grained, porphyritic	-	-	obscured		An_{10}	fairly common	Tremolite, epidote, chlorite, sphene, opaques	Dykes towards the extreme west of the granitic complex Phase (C)?
615	Cream-white, massive, medium-grained, slightly porphyritic	replaced by plagioclase		96-97	An_9	An_9	widespread	Sphene, rutile	The medium to fine-grained granite in the south-west of the complex Phase (C)
609	Grey-white, massive, medium-grained, slightly porphyritic	replaced by plagioclase		obscured		An_{10}	widespread	Rutile	Dykes towards the extreme west of the granitic complex Phase (C)?

such as "porphyritic" to equigranular fabrics and varying shad of red to white colours. They are generally medium-to coarse-grained and all have distinctly embayed quartz grains with elliptical cross-sections, often with bluish hues and similar to the quartz in the porphyroids. The white varieties contain micrographic intergrowths so widespread that they can be referred to as granophyres.

The subhedral to anhedral potassium feldspar grains commo ly show cross-hatch twinning; simple twins, some with sinuous interfaces, are also present. Quartz vermicules are plentiful in the potassium feldspar grains, often in association with micrographic borders around the grains. Plagioclase is sometimes in association both as small, sporadic inclusions in, and as rims around, the potassium feldspar.

Obliquities, measured on the potassium feldspars from thr granites, are found to have the values of near-maximum microcl The subhedral plagioclase grains have generally undergone some decalcification and most tend to be obscured by epidote and wh mica, yet optical measurements giving the plagioclase compositi can be made in certain cases (see Table 16). These determinations, similar to those performed on the plagioclases of the main granite, give a range in composition from andesine to the albite-oligoclase boundary and also reveal that the plagioclase has a high-order structural state.

Lamellar twinning is visible in places, along with traces of both oscillatory and normal zoning.

Quartz is present as pale blue grains possessing elliptic sections with embayments in which feldspar occurs often in optical continuity with adjacent feldspar grains. The quartz has recrystallized in some rocks to mosaics of small grains with sutured boundaries.

The main mafic constituent is biotite, or its alteration products of chlorite, epidote, sphene and opaque minerals. In specimen 616, amphibole occurs partially altered to chlorite.

In the white granites (specimens 615 and 609) most of the potassium feldspar, both in the megacrysts and in the micrographic intergrowths, has been replaced by plagioclase which i distinct from the primary plagioclase in being less altered and often having a chessboard twin pattern.

Petrographical features relating to level of intrusion of the Station Hill Granites.

From the geological history of the area (Chapter 2), the Tennant Creek Granite Complex appears to have intruded unmetamorphosed Warramunga Group rocks, the whole area being subject at a later time to an incipient greenschist facies metamorphis

In accordance with this picture of high-level intrusion, certain petrographical features of the granites investigated i the Station Hill area are similar to those commonly associated with high-level types (Joplin 1964 and Rhodes 1966). These features are -

1. widespread development of "porphyritic" textures,
2. oscillatory zoning in plagioclase (also noticeable glomeroporphyritic groupings),
3. subhedral quartz grains,
4. embayed mineral grains (quartz only in this case), an
5. micrographic intergrowths of quartz and feldspar.

CHEMISTRY.

All analysed granites from Station Hill area of the Tenna Creek Granite Complex have a calcalkaline or peraluminous character (in the sense of Shand, 1951) having corundum as a normative mineral, except for specimen 616 which features one half percent of hornblende corresponding to a few grains occurring in that rock.

Apart from the phase C members, the other granites exhibi relatively little variation in their major element composition (Table 18), comparing favourably with the calc-alkali granite compositions listed by Nockolds (1954).

As well as having slightly higher silica contents, the phase C granites include two granophyres (specimens 615 and 60 in which Na_2O predominates over K_2O, a reverse relationship in comparison to the other granites which have very constant alka ratios (Fig. 16). However, this does not appear to be due to magmatic control, as textural evidence of sodium metasomatism

TABLE 18.

Major element compositions and molecular norms of Tennant Creek rocks -- Station Hill granites.

Specimen nos.	Main granites
632	
510/11	foliated "porphyritic" granites
G	- phase A
621	
	Other granites
608	
607	red granites - phase A(?)
617	
524	pink granite - phase B
619	
616	granites and granophyres - phase C.
615	
609	

ANALYSES AND MOLECULAR NORMS OF TENNANT CREEK ROCKS

	Station Hill Granites foliated				Others							
Specimen	632	510/11	G	621	524	607	608	617	616	619	615	609
SiO_2	70.10	73.93	73.32	71.92	71.48	71.28	72.71	71.32	73.08	75.98	75.62	75.70
TiO_2	0.59	0.35	0.36	0.44	0.51	0.50	0.36	0.51	0.48	0.17	0.50	0.50
Al_2O_3	13.63	13.08	13.42	13.31	13.16	13.37	13.06	13.14	13.25	12.36	13.85	14.13
Fe_2O_3	0.86	0.40	0.48	0.62	0.81	1.07	0.86	1.73	1.08	0.23	0.36	0.21
FeO	3.24	1.86	1.43	2.12	2.50	1.83	1.76	1.71	0.21	1.30	0.13	0.22
MnO	0.05	0.01	0.02	0.03	0.06	0.03	0.04	0.06	0.02	0.03	0.01	0.01
MgO	0.91	0.47	0.38	0.47	0.68	0.86	0.63	0.82	0.56	0.13	0.00	0.06
CaO	1.58	0.97	0.94	1.10	0.99	0.96	0.48	0.88	0.95	0.05	1.64	1.24
Na_2O	2.61	2.73	2.81	2.79	2.36	2.96	2.59	2.78	3.87	2.59	6.63	5.78
K_2O	4.79	5.25	5.36	5.21	5.17	5.01	5.29	5.07	5.01	5.72	0.22	0.68
P_2O_5	0.03	0.06	0.09	0.09	0.13	0.13	0.19	0.16	0.09	0.13	0.03	0.06
Ign. loss	0.80	0.73	0.88	0.94	1.17	1.06	1.23	1.07	0.38	0.52	0.26	0.48
H_2O^-	0.13	0.11	0.10	0.13	0.09	0.09	0.17	0.11	0.18	0.11	0.20	0.17
Total	99.32	99.95	99.59	99.17	99.11	99.15	99.37	99.36	99.16	99.32	99.45	99.24
					Mesonorms							
Q	31.88	34.25	33.07	32.28	35.00	31.81	35.49	32.94	27.86	37.30	30.81	34.70
Or	22.58	28.03	29.61	27.76	26.65	26.16	28.61	27.16	28.20	32.71	1.30	3.15
Ab	24.25	25.15	25.95	25.95	22.10	27.50	24.15	25.90	35.45	24.00	59.70	52.55
An	8.00	4.55	4.20	5.05	4.25	4.05	1.30	3.45	3.90	0.00	6.25	5.85
C	1.48	1.44	1.69	1.46	2.50	1.86	2.97	2.10	0.45†	2.15	0.47	1.96
bi	10.82	6.02	4.78	6.62	8.32	7.18	6.14	6.22	3.20	3.42	0.00	1.44
mt	0.93	0.44	0.51	0.68	0.89	1.16	0.93	1.88	0.77*	0.24	0.30	0.22
ap	0.05	0.13	0.19	0.19	0.29	0.29	0.38	0.35	0.19	0.29	0.05	0.13
											0.05*	
											1.05+	
ΣQ+Or+Ab	78.71	87.43	88.63	85.99	83.75	85.47	88.25	86.00	91.51	94.01	91.81	90.40

present in these rocks.

In trace element content, all the analysed granites, other than the phase C members, have comparable contents of rubidium (195 to 324 p.p.m.), strontium (63 to 93 p.p.m.), barium (429 to 894 p.p.m.) and thorium (23 to 38 p.p.m.).

Relative to the above values, the two granophyres included in phase C (of the granite complex) show enrichment in strontium and depletion of rubidium, barium, and thorium (Table 11) conforming to the marked impoverishment of potassium in these rocks. The remaining two phase C members which do not have low potassium contents show the same trace element pattern, as reported for the granophyres, except for enrichment of rubidium in specimen 619 and barium in specimen 616.

Uranium is uniformly low in all rocks, reaching up to a maximum of 14 p.p.m.

Selected element ratios are listed in Table 11 and their possible significance is discussed later.

Selected Enclaves from the Main "Porphyritic" Granite.

According to Crohn and Oldershaw, (1965) the foliated, "porphyritic" (main) granite may contain up to 30% of its volume of xenoliths which display a variety of types ranging from fine-grained biotite schist to others in which conspicuous porphyroblasts of feldspar and quartz are recorded. Arenaceous enclaves, some with contorted banding, are also mentioned.

During examination of this granite, it was confirmed that some of the enclaves contain megacrysts of quartz and feldspar which show textural similarity to the quartz and feldspar comprising the fabric of the host granite. Accordingly only enclaves containing megacrysts were selected for detailed examination and they are in no way a representative sample of the whole range of inclusions present in the granite.

The samples were obtained from an inclusion-rich area to the north-east of Station Hill at map reference 2,551,000N; 190,000E. Ranging from a few inches to a few feet in length, the inclusions are generally elongate in the foliation surface the host granite. The enclaves themselves are generally folia in a direction parallel to that of the host granite (e.g. specimen 511), but some may be effectively massive (e.g. specimens 629 and 630) where the host granite is least deforme

PETROGRAPHY.

The enclaves bearing megacrysts of quartz and feldspar, range from leucocratic to mesocratic types.

The leucocratic enclaves have a varied appearance from massive, light grey rocks with up to twenty percent megacrysts of quartz and feldspar (specimens 629 and 630, Plate 26a) set in a groundmass with a flecked aspect due to black spindles an irregular patches of biotite 2 to 4 mms. in size in an otherwi leucocratic base, to dense, neutral-coloured, fine-grained typ (specimens 520 and 521) possessing only occasional megacrysts and a foliation of fine mafic wisps or an ill-defined layering of mafic and leucocratic material (specimen 624).

The mesocratic enclaves (e.g. specimens 511, 518 and 519) occur as massive or foliated, dark, fine-grained rocks with prominent megacrysts of feldspar and quartz, set in a groundma in which an interplay between the light and dark minerals ofte produces a distinctive texture. On foliation surfaces, a flecl ing is apparent, produced by fine, irregular to spicule-shaped intergrowths between the light and dark mineralogy (Plate 26c). Normal to the foliation surface, the fabric has a striped pattern with the biotite present as sub-parallel wisps which anastomise and show a tendency to hook back on themselves (Plate 26b).

From the spiculate outlines present in the groundmass, the mesocratic enclaves, at least, appear to be relatively coarse representatives of rocks composed of close-packed fragments of volcanic glass, since recrystallized (c.f. Ross and Smith, 1961).

The Matrix.

The groundmasses are represented by quartz, potassium feldspar and plagioclase in a mosaic of rapidly varying grain size from 0.4 - 0.1 mms.

In the base of the leucocratic enclaves, quartz and potassium feldspar are dominant and have irregular, interlocking boundaries. The plagioclase grains are generally masked by epidote and white mica.

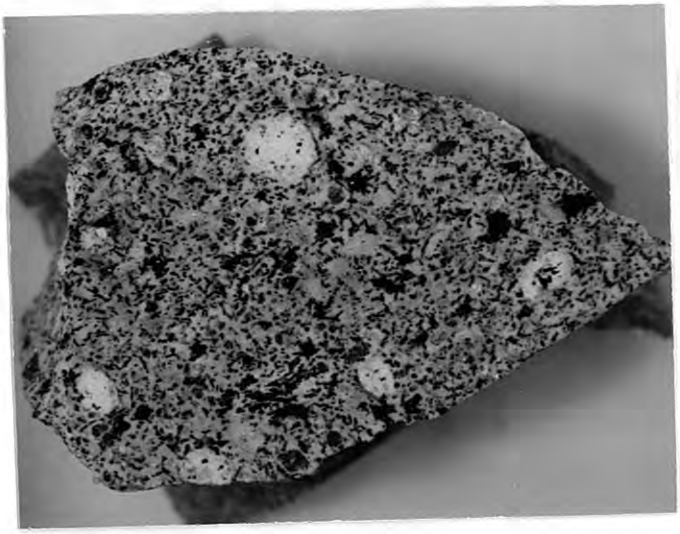
Plate 26 (a)

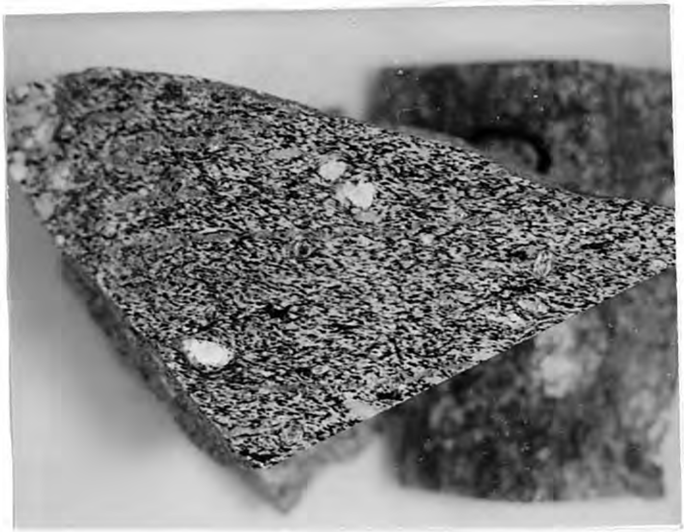
(width of field - 3 inches)

Enclaves of main, phase A Station Hill granite.

Plate 26 (b) - groundmass composed of coarse, recrystallized ash textures (as above).

Plate 26 (c) - groundmass composed of coarse, recrystallized ash textures (as above).





The mesocratic enclaves have groundmasses in which biotit quartz and plagioclase are predominant with potassium feldspar being subordinate in amount. The plagioclase, almost complete masked by alteration products, is present in subhedral grains. The optical identification of plagioclase was confirmed by running X-ray diffraction scans on the groundmasses. Biotite (pleochroic X - straw yellow; Y, Z - dark brown) is present as ragged flakes, either single or in aggregates and can be associated with white mica and opaque grains.

Tourmaline is found in most of the enclaves as small, irregular prisms (0.4 mms. in length) or as partial rosettes. The pleochroic scheme is w > e, E - pale pink or neutral, W - darker, mottled blue, brown and green.

MINERALOGY OF MEGACRYST PHASES.

1. POTASSIUM FELDSPAR.

The large feldspar megacrysts proved to consist of either

a) entirely potassium feldspar with incipient, intermitt ent plagioclase rims, or

b) an irregular core of potassium feldspar surrounded by plagioclase rims of varying width, or, in a few instances

c) entirely of plagioclase, often with a chessboard twin pattern, or as an aggregate of grains slightly disori ed with respect to one another.

Thirteen potassium feldspar megacrysts selected from the enclaves were investigated in the manner described for those of the quartz-feldspar porphyroids and the main "porphyritic" granite.

Texture.

1) Morphology and size.

The potassium feldspar megacrysts found within the enclave are generally 8 to 15 mms. in size and present the same variati in shape as recorded for the potassium feldspars of the host granite. Most of the grains exhibit composite boundaries consisting of both straight and curved edges (Plates 27a and b). A few irregular perimeters occur, but there is little evidence of fracturing.

2) Inclusions.

a) Vermicular quartz inclusions.

As in the granite megacrysts, vermicular quartz inclusions can be viewed microscopically in some potassium feldspar grains of the enclaves (Plate 27a). However, they are not so widespread as in the former.

b) Plagioclase inclusions.

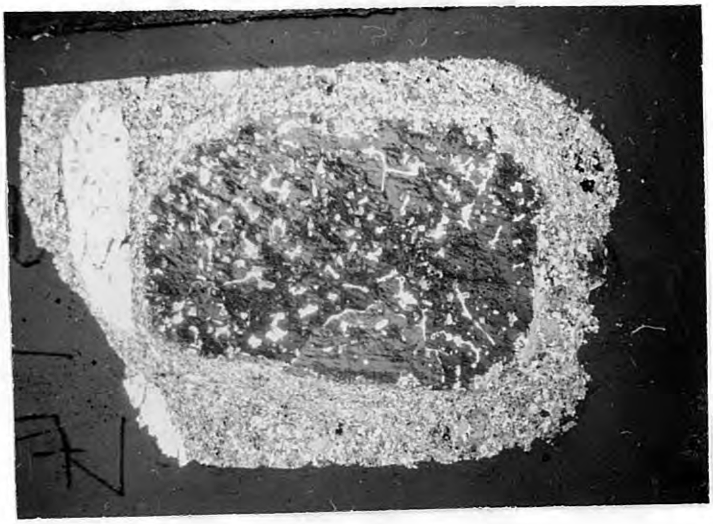
Small plagioclase inclusions are normally present within t potassium feldspar grains. They are similar in shape and size to those occurring in the corresponding feldspars of the granit Their distribution pattern only occasionally suggests a crude, zonal arrangement. It is apparent here that many of the plagio clase inclusions may be regarded as irregular extensions of the

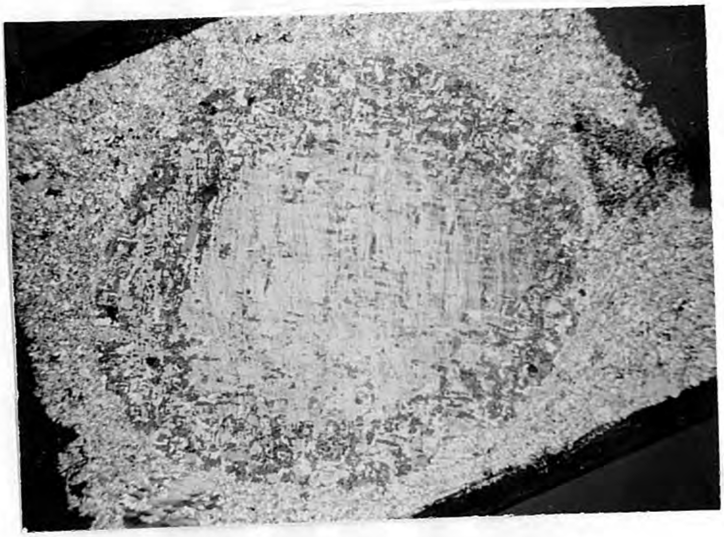
Plate 27 (a) - potassium feldspar with quartz vermicules (width of field - one inch; crossed polars).

Enclave megacrysts of potassium feldspar and plagioclase.

Plate 27 (b) - potassium feldspar with plagioclase mantle (width of field - 2 inches; crossed polars).

Plate 27 (c) - plagioclase megacrysts with synneusis textures (width of field - 3 mms; crossed polars).





wide, plagioclase mantles into the potassium feldspar cores. Both the plagioclase in the cores and in the mantles show zoning of the normal, continuous type.

Occasional plagioclase inclusions of the large variety, (i.e. 2 to 3 mms. long) are present. Although less common here than in the granite feldspars, they are much fresher and exhibit a fine, concentric, compositional zoning of an oscilla tory nature, distinct from the normal zoning in the plagioclas of the mantles and small inclusions.

c) Other inclusions.

As in the granite potassium feldspars; biotite, chlorite, tourmaline, epidote and opaque minerals occur rarely.

3) Plagioclase Mantles.

Plagioclase mantles are almost ubiquitous around the enclave potassium feldspars and range in size from intermitten rims less than 0.5 mms. thick to continuous mantles up to 4 mm wide (Plate 27b). Chess-board twin patterns commonly occur in the plagioclase mantles, which also include irregular blebs of quartz. The inner boundaries of the mantles and cores are characteristically irregular, contrasting with the relatively smooth outer perimeter of the mantle (Plate 27b). This last relationship suggests that the plagioclase rims are of replacement origin. The few large megacrysts composed entirely of plagioclase, may then be due to complete encroachment of the rim plagioclase.

4) Twinning.

Both cross-hatch and occasional, simple twin patterns are recorded in the feldspar grains. The twin laws proved to be Carlsbad; some possible parallel growths were also recorded (Table VIII, Appendix II). Twin surfaces appear as straight or irregular contacts between the usual two sub-individuals. Re-entrant angles are not found.

Optical determination.

The techniques involved in the optical determination of th thirteen potassium feldspar megacrysts are similar to those employed on the potassium feldspars of the porphyroids.

The resulting values of the optical parameters are similar to those of the potassium feldspars of the host porphyritic granite.

The optic axial angle, 2Vx, is between 70° and 90° (Table 3 and Fig. 5), the attitude of the optical indicatrix indicates triclinic symmetry and the refractive index, Nx, has a value of 1.520 (Table IX, Appendix II).

X-ray determination.

Measurement of obliquities (Appendix II), in the potassium feldspar grains reveals a range of values from 0.81 to 0.96 (Table 3 and Fig. 5), indicating near-maximum microcline.

Obliquities probably do not vary greatly within single han specimens judging from the 0.10 range in values encountered amo nine megacrysts measured from hand specimen 519 (Table X,

Appendix II).

Composition.

The thirteen potassium feldspar megacrysts selected from eleven enclave specimens were investigated with regard to the individual compositions, using the $\bar{2}01$ X-ray diffraction tech nique (Appendix II).

The plagioclase in microperthitic relationship is distri within the host potassium feldspar as thin, discontinuous fil similar to those present in the corresponding feldspars of th granite. The amount of plagioclase in this relationship rang from 12 to 20 mol. % Ab + An (averaging 16 mol.%) referring t the increase in plagioclase in solid solution in the host fel spar after heat treatment. The five potassium feldspars havi extensive mantles of plagioclase are included in Table 3 and 5 as a separate group. They show correspondingly larger increases of plagioclase in solid solution and were not included in the estimate of the plagioclase present in perthiti relationship.

The eight remaining potassium feldspars contain up to 6 % Ab + An in solid solution and, when heated and X-rayed rec an average bulk composition of 20 mol. % Ab + An (ranging fr 16 to 26 mol. %).

The compositions of potassium feldspar obtained from the megacrysts of two of the enclave specimens and analysed by X- fluorescence techniques are listed in Table 4. The contents albite are 15.9 and 20.7 mol.%, while those of anorthite are 1.4 and 3.4 mol.%. The relatively large anorthite content of specimen 519 may indicate that not all of the mantle plagiocla was successfully removed from the potassium feldspar separate.

The two values, for the average bulk composition of the potassium feldspar, obtained by the X-ray diffraction and fluo: escence methods are in close agreement (Table XI, Appendix II)

The rubidium, strontium and barium contents were determin as 344 and 307 p.p.m., 96 and 104 p.p.m. and 4,116 and 3,656 p.p.m. respectively.

2. PLAGIOCLASE.

Texture.

Plagioclase feldspar is present mainly as glassy, subhedra megacrysts approximately 4 mms. across.

In thin section, the plagioclase is very similar to that occurring in the host granite and very much less altered. Oscillatory zoning is almost ubiquitous, twin patterns are similar and there are many clear examples of composite grains formed by coalescent growth (Fig. 16c and d, Plate 27c). In many of the simple twins, euhedral oscillatory zoning is seen to deflect across the composition surface of the twin (Fig.16e) indicating a primary origin for the twinning. Carlsbad, albite and pericline twin laws have been recorded.

As already described, plagioclase is also present in a few large megacrysts, possibly pseudomorphous after potassium feldspar.

Optical and X-ray determination.

Measurements on the orientation of the optical indicatrix according to Rittmann and El-Hinnawi (1961 and Appendix III) give the compositions of the plagioclase and also confirm that, in all its textural associations, the feldspar is in a high-order structural state. The closer the plagioclase approaches An50 in composition, the less able is the optic axial angle, 2Vx (Table 17), to resolve the structural condition of the feldspar.

X-ray information is available only on the plagioclase present as possible replacements of the potassium feldspar megacrysts. The separation of the X-ray spectra 131 and $1\bar{3}1$ ranging from 1.61 to 1.69° 2θ is appropriate to the high-order curves in Fig. 9 confirming the optical results.

Composition.

The compositions of the plagioclase determined optically a above are listed in Table 17.

None of the few sporadic plagioclases in the leucocratic enclaves, specimens 521 and 520, were in a suitable orientation to measure their composition accurately.

In the more mesocratic enclaves, the plagioclase is genera andesine, or, in a few cases, labradorite, zoning continuously or discontinuously to oligoclase. As in the granite plagioclase the grains in this environment have delicate, oscillatory zoni

TABLE 17.

Optical data on plagioclase from enclaves in the Station Hill Granite.

Specimen	$2Vx^{o}$	Composition by optics		
Leucocratic				
521	-	An_{28}	G	An_{16}†
520	-	An_{23-20}	I	
Leuco-mesocratic				
629	96	An_{37}	M	An_{20}†
"	-	$An_{39,25,15}$	I	
"	94	An_{38}	R	
630	96	An_{38}	M	
"	-	An_{23}	G	
"	-	An_{37}	R	
Mesocratic				
624	100	An_{56-41}	M	
"	99	An_{43-25}	M	
"	-	An_{37-25}	I	
514	96-99	An_{37}	M	
"	-	$An_{52,37,25}$	G	
"	-	$An_{37,27}$	I	
"	98	An_{37}	R	
625	99-100	An_{36}	M	
"	97	An_{37}	I	
"	-	An_{38}	R	

TABLE 17 contd.

Optical data on plagioclase from enclaves in the Station Hill Granite.

Specimen	$2Vx^o$	Composition by optics		
511	96-99	An_{40}	M	An_{26}†
"	98	$An_{40,31}$	I	
"	99	$An_{37,32,26}$	I	
519	96	An_{37}	M	
"	-	$An_{38,28,23}$	I	
"	-	An_{33}	R	
518	98	$An_{40,26}$	M	
"	-	An_{40-27}	G	
"	-	$An_{40,25}$	I	
509	97	An_{40}	M	
"	-	An_{40}	G	
"	-	$An_{40,37,24}$	I	
505	98	An_{43}	M	An_{32}†
"	-	An_{35}	G	
"	-	An_{39}	I	

M - megacryst, G- grain in groundmass, I- inclusion in large megacryst, R- rim of large megacryst.

† normative value.

with, in this case, variations of up to 8% An.

The plagioclase included in the potassium feldspar megacry tends to be oligoclase in the leucocratic enclaves and andesin often zoning continuously or with a break to oligoclase in the more mafic enclaves.

The mantle plagioclase in the leucocratic types is masked alteration, but in the mesocratic enclaves the large mantles (and pseudomorphs) are andesine, sometimes zoning to oligoclas

The groundmass plagioclase is not always determinable, bu appears to be oligoclase in the leucocratic enclaves and labradorite to andesine which may zone to oligoclase in the me cratic types.

3. QUARTZ.

The quartz megacrysts are approximately 6 to 10 mms. in size and show a tendency to have elliptical outlines. Embayme and internal cavities are present, similar to those of the quartz grains, in the porphyritic granite and the porphyroids.

CHEMISTRY.

Analyses of four enclaves from the Station Hill Granite, comprising two leucocratic and two mesocratic varieties are listed in Table 17. The more acid members of the group (speci- mens 521 and 629) compare favourably in composition with calc-alkaline rhyolites, while the mesocratic samples (specimens 51 and 505), approach rhyodacitic compositions.

As the silica content increases from 68% in the most basi to 75% in the most acid variety, there is a gradual change in major element composition of the enclaves with decreases in Al_2O_3, CaO and total Fe_2O_3 plus MgO (total iron being expresse as Fe_2O_3 in the analyses), while total alkalies show an increa in amount (although Na_2O decreases slightly). The rocks are characterized by normative corundum.

The more basic enclaves have a greater amount of normativ biotite which is in accord with qualitative petrographic observation.

Towards the more acid members of the analysed enclaves, there is an increase in the concentration of rubidium (151 to 236 p.p.m.) and barium (616 to 987 p.p.m.) and a decrease in the strontium content (96 to 55 p.p.m.).

Element ratios listed in Table 11 are commented on in due course.

CHAPTER 8.

PETROGENESIS OF THE QUARTZ-FELDSPAR PORPHYROIDS.

ORIGIN OF THE MEGACRYSTS.

Existing Explanations.

The origin of the megacrysts and the rocks in which they occur has been the subject of a controversy based on the proposal by J. Elliston (1965, 1966 and 1968) that the mineral grains are of authigenic* origin within sedimentary rocks.

In an all-embracing theory, Elliston proposes the genesis at relatively low temperatures of ore deposits by the concentration of metal ions in certain sediments, subsequent expulsion from the source rock, transport in a finely-divided colloidal suspension and concentration in water extrusion channels to form ore bodies. The theory relies heavily on processes governing the behaviour of substances in the colloidal state, involves massive retexturing of suitable sediments during slumping or disturbance with the segregation of the

* Strictly speaking, authigenic minerals are those which have grown in situ within rocks whether they be igneous, metamorphic or sedimentary. However, the term "authigenic" as applied to minerals, is most commonly used to refer to those which have formed in situ in sedimentary rocks during diagenesis and it is used here in that sense.

naturally contained, colloidal material and adsorbed metal ions into globules (and their fracture fragments) sitting in a granular or detrital matrix. During subsequent lithificati and diagenesis, the gel globules dehydrate and crystallize expelling the metal ions as insoluble, metal hydrosols and producing syneresis* or shrinkage crack patterns which give t resulting grains of quartz and feldspar a honeycombed, embaye aspect and conferring on the rocks an igneous appearance.

After petrographic examination of the rocks in thin section, both Nashar (1965) and Fander(1965) supported Elliston in suggesting that the megacrysts were of authigenic origin within a sediment. However, Nashar was of the opinion that most of the quartz and feldspar grains were formed by recrystallization of the matrix of the rock during the green-schist facies metamorphism, although some of the grains still bore evidence of syneresis cracks inherited from colloidal processes.

Elliston's hypothesis was rejected by Spry (1965) who proposed, mainly on the basis of petrographic arguments supported by a few rock compositions, that the megacrysts in the porphyroids were of magmatic derivation with the containir rocks being associations of lavas and pyroclastics.

* syneresis is the concentration of a colloidal gel with liber tion of the dispersion medium.

Mode of Origin.

On the basis of groundmass textures and bulk rock compositions, the quartz-feldspar porphyroids are considered to be fragmental rhyolitic volcanic rocks probably of ash-flow origi which have undergone greenschist facies metamorphism.

Thin section examination reveals that the megacrysts are pre-tectonic to the foliation, which was synchronous with the regional metamorphism, having the mineral alignment winding around the megacrysts producing pressure-shadows.

The above hypotheses cover all possible explanations for the origin of the megacrysts and are considered under three alternatives which may be expressed in two groups as follows -

1. in which the megacrysts are derived, in company with the groundmass, from a magmatic source in which they were present as phenocrysts, or
2. in which the megacrysts have grown in situ in sedimentary or pyroclastic rocks as a result of
   a) diagenetic alteration or recrystallization, or
   b) greenschist facies metamorphism (the period of growth being, of necessity, pre-tectonic.

Textural Considerations.

1. Habit.

It is immediately apparent that in habit the megacrysts of quartz and feldspar occurring in the porphyroids are dissimilar to authigenic quartz and feldspar documented in sedimentary rocks (Baskin, 1956) and tuffaceous rocks (Hay, 1966). Hence, Baskin indicates that most authigenic potassium feldspars tend to be microscopic in size, comprise only a few percent by volume of the rock, possess an altered, detrital nucleus in each otherwise clear grain and generally have euhedral crystal outlines. None of these features are applicable to porphyroidal, potassium feldspars.

These textural criterial also apply to authigenic albite (Baskin, 1956, and Dapples, 1967) and quartz (Topkaya, 1950, and Deer, et al., 1963) and are not present in the albite (with the exception of euhedral outlines) and quartz megacryst of the porphyroids.

On the other hand, honeycombed and embayed mineral grains are fairly common in volcanic and other high-level igneous rocks (Joplin, 1964 and Jacobson, et al.,1958). Ovoid shapes as assumed by some of the potassium feldspar grains in the porphyroids, have been recorded in the extensive literature on rapakivi granites, reviewed by Tuttle and Bowen (1958), althoug the intensive embayment and sieve textures similar to those in the porphyroidal potassium feldspars are apparently absent

(Savolahti, 1962).

Embayed mineral grains are rare in metamorphic rocks occurring only in some hornfelses which contain evidence of a former abundance of intergranular fluid (Spry, 1969, p.156).

However, according to Elliston (1968), certain textural features of the megacrysts have implications which contradict an igneous origin and lend strength to his hypothesis that the mineral grains have grown from colloidal material during diagenesis. The most important of these, together with the implications drawn by Elliston, are paraphrased in parenthesis and discussed below.

a). "The drawn out shapes or 'tails' of the mineral grains and their mutual indentations at points of contact are evidence for a soft stage in the history of the material comprising the megacrysts."

Thin section study indicates that the drawn out shapes and 'tails' of some of the mineral grains are due to granulati and recrystallization of the quartz and feldspar along the foliation surface defined by the phyllosilicates. The majorit of the grains are not granulated but have undulose extinction and pressure-shadows in which the matrix grain has coarsened. On the rare occasions when two megacrysts are in contact, one tends to be deformed around the more resistant member.

These features are typical of rocks deformed and metamorphosed under low-grade greenschist facies conditions (see Stauffer, 1967), and are not appropriate to sediments which have undergone deformation in an unlithified state, as suggest by Elliston.

b). "The crystals have ovoid or spherical shapes with concentric, internal structures paralleling the rim. These grain shapes are not due to corrosion which would randoml transect the internal structures."

The megacrysts of potassium feldspar have habits (as described in Chapter 3) in which both the curved and straight sections o the grain edges (the former more than the latter) may have a parallel zone of cavities (referred to by Elliston above as "internal structures") just inside the perimeters. These cavities (along with others in the core) are considered to be an internal expression of the narrow embayments in the grain perimeters(Chapter 3). It will be shown later that if the zone of cavities is produced during the same act of corrosion as is responsible for the curved edges of the grains, no transection of the former by the latter need occur.

The quartz grains exhibit the radial, more than the concentric distribution of embayments and cavities; the plagiocla is not embayed at all.

c). "The embayments which often show a radial and concentric distribution are interpreted as syneresis textures, i.e. shrinkage cracks formed during concentration and contrac tion of gelatinous material undergoing dehydration or lo of its dispersion medium."

This is merely a subjective interpretation as Elliston has not clearly indicated the criteria by which he identified the embayment and cavity textures in the quartz and potassium feldspar megacrysts of the porphyroids as being due to synere and hence different in origin from those recorded in some of the mineral grains of undoubted magmatic rocks (Joplin, 1964)

d). "The globular crystals may be composed of individuals often with sutured joining surfaces. There is no mechan to produce this under igneous conditions."

It has been shown that those composite grains of potassi feldspar have sub-individuals mutually related by twin laws of the Carlsbad and Baveno types which are commonly encounter in potassium feldspars from igneous rocks.

Hence, contrary to Elliston's assertions, none of these textures appears incompatible with an igneous origin.

From the relict bubble and perlitic crack patterns preserved in the mineralogy of the embayments and cavities of some of the potassium feldspar grains, it may be deduced that these embayments and cavities, and presumably those in the quartz grains, once contained a silicate glass formed from a viscous melt and hence were present during the magmatic phas of the pyroclastic rocks.

As described elsewhere, the plagioclase is not characterised by embayments and cavity textures. The grains are subhedral, often formed of various sub-individuals giving "blocky outlines with re-entrant angles. This suggests that these grains may have originated by coalescence in an igneous melt i a similar manner to the composite plagioclase grains in the Station Hill Granite and enclaves. In the general absence of oscillatory zoning, this cannot be verified as in the case of the granite and enclave plagioclases. However, as describec in Chapter 3, a few of the grains are of andesine composition and contain traces of a fine oscillatory zoning which supports an igneous derivation at least for these grains. All plagioclase outlines appear too well-shaped to have formed as porphyroblasts during the greenschist facies metamorphism.

The irregular shapes of some of the potassium feldspar grains may then be ascribed to fracturing during extrusion of the pyroclastics. Grain fragments are present in all rocks irrespective of degree of development of the foliation. This fracturing is distinct from that produced in situ by shearing along the foliation surface of the porphyroids where the vario fragments may be easily matched and the original shape of the grains reconstructed. The complete absence of embayments on the fracture surfaces of the potassium feldspar grain infers that the embayments were present prior to transport in a fluid ized condition and did not develop subsequently.

The quartz and plagioclase grains which are smaller are normally complete.

In summary, the habits of the megacrysts in the porphyroi rocks are different from those commonly attributed to authigen minerals or to minerals of greenschist facies metamorphic rocks and possess distinct similarities to certain mineral grains recorded in high-level igneous rocks.

2. Twin Relations.

Twin patterns in feldspars give information of some significance in deciphering the origin and history of these minerals.

a). Potassium feldspar.

Least diagnostic because of their wide distribution are the cross-hatched twin patterns, which are ubiqui tous in the porphyroidal microclines and which are widely regarded, following Laves (1950), as indicatin transformation from less-to more-ordered structural states and infer that the potassium feldspar initial formed in a monoclinic condition. Most microclines have this characteristic twin pattern, except for a few occurring in low grade schists (Barth, 1969), an pegmatites (Barth, 1969) and some authigenic varieti which have fourling twin patterns; these occurrences indicating primary growth as triclinic modifications The presence in the porphyroids of some potassium feldspar grains showing simple twinning on the Carls- bad and Baveno laws reveals that the K-feldspars have the same twin laws as those recorded from igneo rocks by Dolar Mantuani (1952) and Ingerson (1952) ar do not have the fourling twin pattern found in authi- genic potassium feldspar (Baskin, 1956 and Perrenoud, 1952).

According to Van der Plas (1966), the presence of Carlsbad, Manebach and Baveno twin laws in potassium feldspars indicates their igneous origin and, moreove they may be expected to retain these twin patterns through greenschist facies metamorphism.

The characteristic irregularity of the interpenetrant twin composition surfaces already described in the porphyroidal potassium feldspars is worthy of comment as Priem (1962) states that Köhler (1948) has attribu this phenomenom in Carlsbad-twinned microcline to for

tion in high-temperature silicate melts. However, th
nature of the evidence for this relationship remains
unknown.

Hence the twin patterns suggest an igneous origin for
the potassium feldspar grains of the porphyroids rath
than an origin under low grade metamorphic or authige
conditions.

b). Plagioclase.

No comprehensive, statistical study was made of the t
patterns (see Gorai, 1951, Turner, 1951 and Tobi, 196
developed in the plagioclase feldspars as distinguish
ing the twin law is often difficult (between albite a
carlsbad twinning, for example) in the albite composi
tion range (Tobi, 1959).

Twin laws, positively identified on the universal sta
by the method of Slemmons' (1962a), are albite and
pericline, and carlsbad and albite-carlsbad; A - and
twins respectively (after the terminology of Gorai,
1951).

Both A - and C - twins are found in the plagioclase c
igneous rocks as well as that of greenschist facies
rocks (Tobi, 1962) and are distinct from the fourling
twin patterns recorded in authigenic albite (Baskin,
1956, Deer, et al., 1963 and Barth, 1969).

Pericline twins are not characteristic of albite from greenschist facies rocks as twins with a composition surface other than (010) are rigorously absent (Tobi, 1962).

The recognition of secondary lamellar twinning caused by deformation in the albites is based on the criteri of Vance (1961) and, if valid, indicates that the alb has undergone structural and/or compositional changes Secondary deformational twinning is not considered to be possible in completely-ordered albite because of t difficulty of rearranging Si and Al atoms in the latt (Laves, 1952, Smith, 1962, Vogel and Siefert, 1965). Therefore its existence in the porphyroidal albites suggests that the plagioclase was originally in a mor disordered structural condition and/or had a more calcium-rich composition (probably andesine, in agreer with the presence of the few relict andesines still preserved) which implies a magmatic origin for the plagioclase grains.

Chess-board twin patterns are common in albite replacing megacrysts of potassium feldspar in the Creek Bed Porphyroid and frequently preserve remnants of the embayment geometry ar the Carlsbad and Baveno twin patterns present in the original potassium feldspar. Similar relationships were observed by Starkey (1959) who attributes the origin of chess-board patterr in the albite replacing the microcline of some regionally meta-morphosed (greenschist facies) porphyries to the combined eff of replacement and deformation. Chess-board twin patterns hav no relevance in deciding among the various hypotheses propose for the origin of the megacrysts.

The limited evidence available from the plagioclase twinning points to an igneous derivation for the plagioclase mineral grains.

Structural State of the Feldspars.

Structural information on the feldspars is of no value in deciding among the three hypotheses.

The work of Dietrich (1962) indicates that the obliquity (Δ - value) of the K-feldspars is not diagnostic of any partic paragenesis. High obliquities such as those present in most c the porphyroidal K-feldspars are typical of K-feldspars in met morphic rocks of the amphibolite facies and lower and, if the obliquities were originally low (as can occur in both volcanic and authigenic K-feldspars, Dietrich, 1962 and Baskin, 1956), the greenschist facies metamorphism could have ordered the K-feldspars.

In the case of albite, the completely-ordered condition found in the porphyroidal plagioclases is typical of greenschi facies metamorphic rocks and most other occurrences (Barth, 19 with the exception of certain authigenic albites (Barth, 1969 and Baskin, 1956).

The structural states of the feldspars are discussed further in a later section in the light of the proposed origir of the porphyroidal megacrysts determined from more diagnostic information.

Composition.

In accordance with their low-temperature origin, authigen feldspars are relatively pure. Hence, authigenic potassium feldspar is perthite-free, the Na_2O content rarely exceeding 0.3 wt.% (Baskin, 1956 and Carozzi, 1960). This is in distinc contrast to the porphyroidal potassium feldspars listed in Tab 4, which are perthitic and have Na_2O contents, all of which ar over 1 wt.% and some over 2 wt.%.

The amount of anorthite in authigenic albite is normally not greater than 1 mol. % (Deer, et al., 1956 and Carozzi, 196 which is exceeded by most of the porphyroidal plagioclase comp sitions determined optically.

Little information has been found in the literature pertaining to the trace element content of authigenic feldspars. However, Horstmann (1957) notes that the recrystallizatio of illite to potassium feldspar results in the preferential exclusion of rubidium and Reynolds (1963) has shown that authi genic K-feldspars are depleted in rubidium relative to potassi having K/Rb ratios in the range 500 to 1000. Most K-feldspars from granitic rocks, both magmatic and metamorphic, fall withi the range 440 to 150 (Heier and Taylor, 1959).

The porphyroidal potassium feldspars have K/Rb ratios in the range 263 to 410 (Table 21), well within the accepted ran of K-feldspars from granitic rocks but not appropriate to authigenic K-feldspars.

Hence, in terms of potassium, sodium, calcium and rubidi the compositions of the porphyroidal K-feldspars are differen from those of authigenic K-feldspars.

The albite contents of potassium feldspars in igneous rocl vary over a wide range. Hence, Rhodes (1969) has recorded a range of 50 to 8 mol. % albite in K-feldspars from selected Australian granites. The anorthite content varies very littl generally being lower than 5 mol. %. From experimental data, Tuttle and Bowen (1958, Fig.11) have shown that the albite content of potassium feldspars may be correlated with temperature. This gives a series of minimum temperatures of formatic ranging from magmatic values at the highest albite content to sub-magmatic values typical of the greenschist facies of metamorphism at the lower albite contents. The K-feldspars of porphyroids have albite contents in the lower part of the range, i.e. from 12 to 24 mol. % albite, corresponding to minimum temperatures of formation of approximately 400 to 500° C.

The albite composition of most of the plagioclase in the porphyroids is appropriate to greenschist facies metamorphic rocks (Barth, 1969).

Therefore, in composition, the porphyroidal feldspars are similar to those of greenschist facies metamorphic rocks.

In conclusion, as regards the origin of the megacrysts of the quartz-feldspar porphyroids :

a) the habits and twin patterns support an igneous origi for these mineral grains,

b) the structural condition of the feldspars is inconclu sive, and

c) the present composition of the feldspars is distinct from that of authigenic varieties and reflects metamorphic (greenschist facies), rather than magmatic, temperatures.

Therefore, the textures are consistent with an igneous derivation for the megacrysts (as they are for the groundmasse of the rocks) rather than one involving diagenetic or low grad metamorphic recrystallization of the fragmental bases of the quartz-feldspar porphyroids. The compositional features of the mineralogy are discussed later.

Origin of the Embayment and Cavity Textures.

Two hypotheses have been proposed to account for embaymen in crystals of igneous rocks. The first regards the shape of grains as being due to irregular or amoeboid growth (Vogt, 193 and Rittmann 1962), while the second considers the embayment geometry to be the result of resorption (Judd and Cole, 1883) and hence to be later and distinct from the growth period.

It is possible to resolve this question unambiguously only where relationships between embayments and definite growt zones are clearly expressed. In this way, Vance (1965) and Stevenson (1947) have demonstrated partial dissolution of plagioclase grains by observing the truncation of compositiona growth zones by embayment channels. On the other hand, the work of Blackbery (1968) on certain plagioclases provides evi-dence for limited, irregular growth as compositional zoning runs parallel to embayment edges.

In view of the above, the mode of formation of the embayment geometry in either the potassium feldspars or the quartz of the porphyroids, cannot be determined conclusively in the absence of identifiable growth zones.

Etch and stain tests failed to reveal any traces of compo sitional or growth zoning in the potassium feldspar or quartz of the porphyroidal rocks.

Parts of the potassium feldspar and quartz megacrysts wer subjected to large area scans by an electron-probe analyser and X-ray photographs were taken by the Cambridge Instrument Company Ltd. to show the distribution patterns of various elements. However, the distribution of K, Na and Ca in the potassium feldspar (no Rb, Cs or Pb were detected) and that c Al and Ge in quartz (no Sn or P being detected) revealed no recognisable zoning.

It is worthwhile to acquire information on both irregular growth and resorption processes by observing the resulting geometry of grains occurring in situations where the mechanism of formation is known, with a view to establishing possible textural criteria to distinguish between the two processes.

Irregular growth.

From a review of the growth of crystals in artificial mel Drever and Johnson (1956) confirmed that under conditions of undercooling, olivine grains, mostly of skeletal aspect, were obtained. Buerger (personal communication in Stevenson, 1947) found from his work on synthetic minerals, that under conditio of rapid crystallization, lineage structure developed giving irregular growth patterns. In a study of the growth of crysta of simple salts, Buckley (1951) featured crystal habits with dendritic, spherulitic and hollow configurations produced by the addition of impurities to the system.

Hence, it appears likely that when conditions favour irre lar growth, skeletal or dendritic patterns are produced in whi the resulting cavities tend to have the regular edges of "nega crystals".

Resorption.

Detail on textural patterns resulting from the dissolutio of crystals comes from a variety of sources.

From a study of plagioclase grains showing resorption features (proven by their relationship to compositional growth zoning) in igneous rocks, Vance (1965) has arrived at some conclusions regarding the nature of resorption and suggests that "intense corrosional channeling of the interior of the cores and relatively weak attack of their outer portions is characteristic of the resorption process".

Additional confirmation that partial solution may result in intricate embayment patterns within the body of the grains is available from both natural and experimental sources, such as :

a) from partially fused quartzose, feldspathic and grani xenoliths in basaltic andesite from New Zealand, (Steiner, 1958),

b) from granite partially fused by a plug of basaltic andesite in the Sierra Nevada, California (Al-Rawi an Carmichael, 1967), and

c) from experimental studies on the anatexis of granite samples (Kranck and Oja, 1960, Plate 1, Fig. 4).

In all of these occurrences, the resulting embayment orientation is partially controlled by the cleavage of the minerals.

It is reasonable to assume, in company with Vance (1965) that the shape of the crystal grains during resorption will be controlled by surface-energy relationships on the corrosional interface. As the grain shapes may be expected to comply with minimum energy requirements, any parts of the crystal lattices having relatively high energy, will be more unstable and will dissolve before the other parts. In this manner, the resorpti geometry will be controlled in the early stages by any feature causing a slight increase in lattice energy, such as :

a) impurities, inclusions or holes (Volmer and Schmidt, 1937),

b) twin surfaces (Kretz, 1966),

c) defect structures, such as dislocations or stacking faults, and

d) growth zones.

Although conclusive proof is not available, it appears that, in general aspect, the embayment geometry developed in the potassium feldspar and quartz of the porphyroids is differ from the more regular skeletal or dendritic patterns which result from irregular growth.

Furthermore, the textural features of the potassium feldspar grains are consistent with the patterns associated with resorption effects as outlined by Vance (1965). As already described, the curved perimeters, which allow some of the megacrysts to approximate to circles or ellipses in cross-section, generally possess a greater concentration of embayments in comparison with the straight edges. This close association of curved edges and embayments suggests that they are genetically connected and is consistent with both :

a) overall, weak corrosion of the stable shell represent by the crystal perimeters with modification of the euhedral grain habit by rounding of the corners with preservation of straight edges, and

b) associated, narrow embayment channels leading into th grain interiors, representing selective, internal corrosion, presumably after breaching of the crystal boundaries by the melt phase.

The tendency for the embayments to run parallel to cleava in the potassium feldspar grains is also expressed in the reso tion patterns already reported from the literature. The preference for the cavities and channels to follow the interfa of simple twins may be explained by the higher energy of these sites leading to preferential solution by the melt, as outline above.

The tendency for cavities to concentrate in a zone genera parallel to, and just inside, the grain perimeters, be they curved or straight, may be due to the resorption process being influenced by otherwise undetectable growth zones, which would normally be parallel to the crystal habits of the unmodified mineral grains. This could lead to parallelism between the cavity zones of the megacrysts and the perimeters, as the latt will, in the early stages of resorption, differ from their original shape only in having rounded corners.

Just as the final growth habits of crystals are partly controlled by the lattice structure of the constituent mineral so the shapes produced during resorption may also be expected to be influenced by structural features of the mineral grains.

INTERPRETATION OF COMPOSITIONS.

Relation of the quartz-feldspar porphyroids to the synthe granite system.

Most of the analysed quartz-feldspar porphyroids have the sum of their normative quartz, orthoclase and albite greater tl 80%. The mesonorms in Table 10, recalculated to weight percent (after Hall, 1966c) are plotted on a projection of the syntheti granite system Q + Or + Ab + H_2O (Fig. 19) as determined by Tuttle and Bowen (1958).

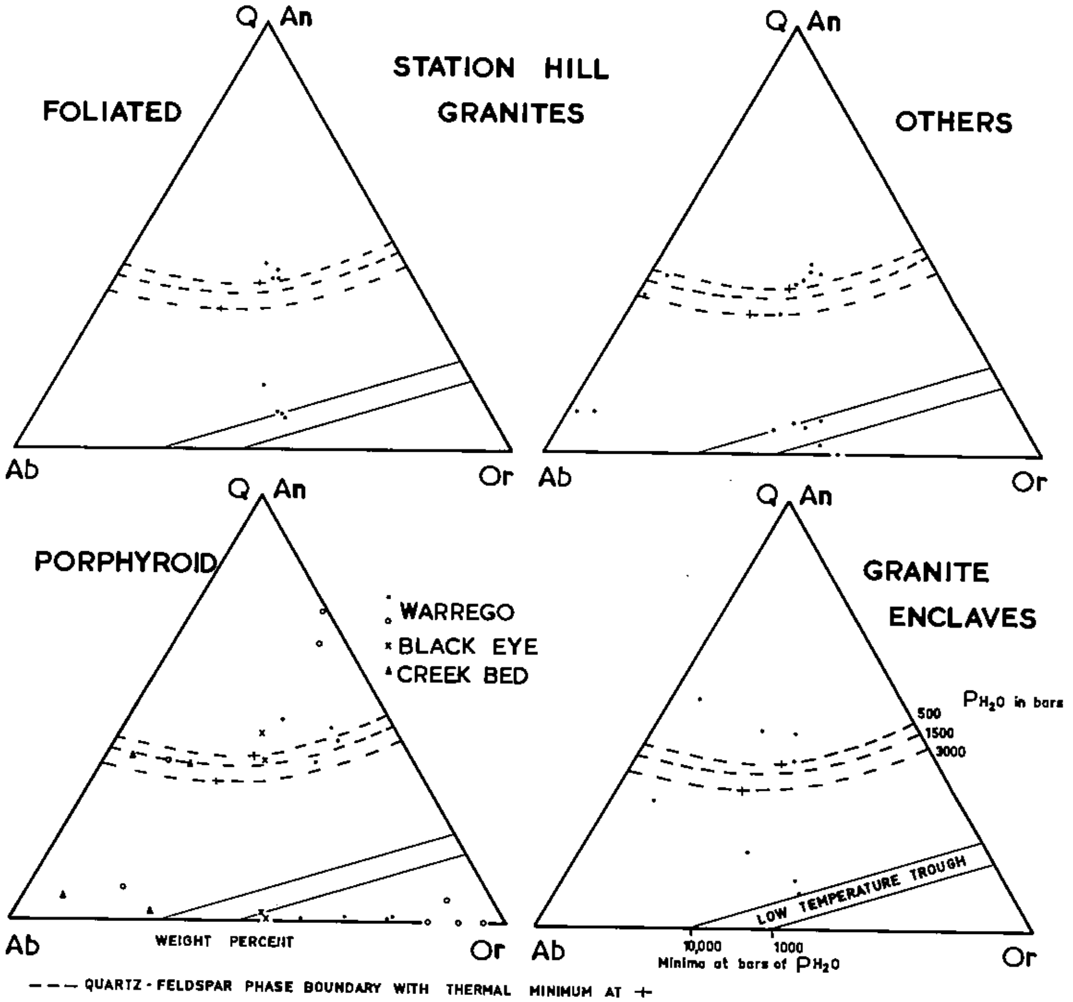
All of these porphyroids, with the exception of the Warreg Group B samples (see Chapter 3), are spread on or near the quartz-feldspar boundary trough. The two Black Eye specimens plot in the vicinity of the thermal minimum on the quartz-felds boundary for 500 bars water vapour pressure. The other Group A samples are distributed on either side of the Black Eye represe

Figure 19.

Nomative plots of selected Tennant Creek rocks on composite diagrams of the systems Q-Or-Ab and An-Or-Ab (in the porphyroidal diagram -

. represents Warrego Group A samples

o represents Warrego Group B samples).



Normative plots of selected Tennant Creek rocks on composite diagrams of the systems Q-Or-Ab (TUTTLE & BOWEN, 1958) and An-Or-Ab (KLEEMAN, 1965) tives according to their normative albite to orthoclase ratio. Hence four out of five Warrego specimens are potassium-rich, while the exception (specimen 94) plots with the two Creek Bed samples which are sodium-rich, relative to the Black Eye specimens.

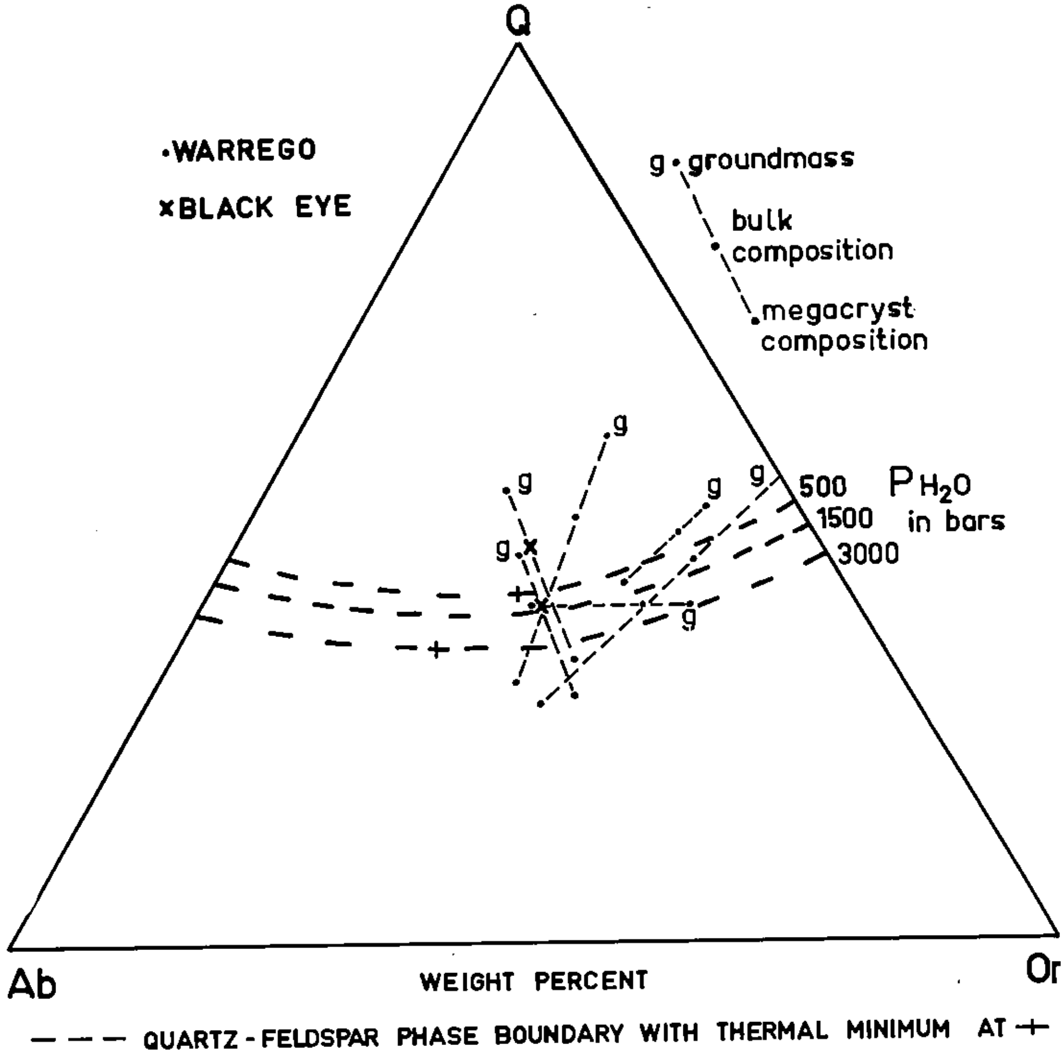
In terms of normative quartz, potassium feldspar and albi the compositions of the porphyroidal groundmasses were obtaine by subtracting the compositions of the megacryst material from the bulk compositions of the rocks. The results are plotted i Fig. 20 for the Black Eye samples and the potassium-rich Group A Warrego samples and illustrate that, whereas the megacryst compositions of most of the porphyroids and the groundmass compositions of the Black Eye representatives fall in the cent part of the triangular diagram of the granite system Q-Or-Ab-H (the part which contains the composition of residual liquids at the thermal minimum), the groundmass compositions of the Warrego specimens do not have this characteristic.

Strictly, the Black Eye matrices are slightly enriched in SiO_2 relative to the thermal minimum, while those of the Warrego Porphyroid are substantially enriched in K_2O and to some extent, in SiO_2. Hence, the removal of the bulk composi of the Warrego samples from the centre of the diagram towards the Q - Or sideline, is seen to be a function of the groundmas rather than of the megacrysts.

Petrographical examination has revealed that both samples

Figure 20.

Calculated compositions of porphyroidal groundmasses plotted on a diagram of the system Q-Or-Ab.



Calculated compositions of porphyroidal groundmasses plotted on a diagram of the system Q - Or - Ab (TUTTLE & BOWEN, 1958) of the Creek Bed Porphyroid and Warrego specimen 94 have most of their potassium feldspar megacrysts replaced by plagioclase No such pseudomorphous relationships are obvious in the ground masses. Potassium feldspar has been detected optically only in the matrix of one Creek Bed sample (specimen 602) and does record on an X-ray diffraction scan of the groundmass of specimen 94. Hence, the relatively high sodium to potassium ratio, which causes these three samples to plot towards the Q - Ab sideline in Fig. 19. may be explained in terms of the replacement of potassium feldspar by plagioclase in the megacr and probably in the groundmass also.

The Warrego Group B Porphyroids, whose compositions are remote from the thermal minima in the granite system, (Fig.19) plot near the Q - Or sideline well into the quartz field (specimens 12 and 35) or close to the Or apex (specimen 249).

The CaO content of the quartz-feldspar porphyroids.

As already mentioned, a feature of the composition of the quartz-feldspar porphyroids, when compared with Nockolds' aver rhyolite (CaO being 1.13%), is the very low CaO content of the Warrego and Black Eye representatives (CaO between 0.15 and 0. Table 10) while the Creek Bed rocks have a higher content (CaO being 0.74 and 0.40%). As a result, when the compositions of the quartz-feldspar porphyroids are plotted in terms of their normative feldspar components on the Or - Ab - An projection o the silica-saturated surface of the system Or - Ab - An - SiO_2

discussed by Kleeman (1965), all of the rocks lie very close to the Or - Ab sideline and, with the exception of the Black Eye representatives, are not closely related to the low-temperature trough (Fig. 19), the potash-rich samples falling well into the potassium feldspar field.

The low CaO value gives a normative plagioclase value of sodic albite in the rocks which is in agreement with the albit composition of the plagioclase megacrysts as determined optica The groundmass plagioclase, where present, is also expected to be albite in composition.

Where the CaO content is highest, the Na_2O to K_2O ratio i also highest (i.e. in Warrego specimen 94 and in the two Creek Bed samples) so that the normative plagioclase remains albite.

Three main factors which may be supposed to have an influ on the composition of fragmental, volcanic rocks are :

1) magmatic processes,

2) mode of eruption, and

3) secondary processes.

Their relevance to the present pattern of compositions is discussed in turn.

1) <u>Magmatic processes</u>.

Studies of young, unaltered, acid volcanics by various wo indicate that in composition these rocks show an approach to tl of residual magmatic liquids in the granite system Q - Or - Ab H_2O investigated by Tuttle and Bowen (1958). This is characteristic of Recent rhyolitic obsidians from Glass Mountain, California mentioned by Battey (1955), of Tertiary rhyolites discussed by Carmichael (1963), of Tertiary rhyolitic ash-flow sheets from Nevada (Lipman, 1966) and of Pleistocence to Recent rhyolites of the Taupo Volcanic Zone (Ewart, et al., 1968 a and b).

As indicated, only the bulk compositions of the two Black Eye specimens plot close to the thermal minima of the synthetic granite system at low water pressures. This strongly suggests that these rocks have a magmatic origin involving crystal-melt equilibria. However, there seems little possibility of explaining the range in positions of these porphyroids in Fig. 19 by any known magmatic process. Certain factors are known on an experimental basis to influence the composition of residual liquids in the granite system.

The work of Luth, et al., (1964) has shown that with increasing water pressures the composition of the residual liquids in the granite system Q - Or - Ab - H_2O becomes more sodium-rich as the minimum moves towards the Ab apex. High water pressures, however, cannot explain the soda-rich porphyroids as they have compositions which fall in the low-temperature trough along the quartz-feldspar boundary for low water pressures and does not account for the potassium-rich samples.

Melting experiments carried out by Von Platen (1965) on natural material infer that the greater the amount of normativ anorthite relative to albite present in acid melts, the more t composition of the residual liquids will be enriched in normat quartz and orthoclase. Assuming that the rocks may be calcium poor as a result of secondary processes, it is perhaps conceiv that their original content of normative anorthite could have given residual liquids similar to the bulk composition of the potash-rich porphyroids. However, this is not considered like as the groundmasses of these rocks show a wide spread of compo sitions and, at least one is enriched in potash to such an ext that it plots on the Q - Or sideline (Fig. 20), a position tha is hardly compatible with a magmatic composition. Also, this does not account for the sodium-rich representatives.

Certain late stage rocks such as pegmatites and potash aplites (Nockolds, 1947) appear to have compositions approachi those of the potash-rich porphyroids. It has been suggested (Tuttle and Bowen, 1958 and Krauskopf, 1967) that rocks such a these may be derived from residual granitic melts by the actio of excess alkalies in increasing the solubility of water in th melt and allowing the latter to remain mobile down to at least 400^{o} C.

However, such late stage rocks are by nature highly fract ated and consequently should have anomalously low K/Rb ratios (Taylor, 1965). This is not the case with the porphyroids as n of them have abnormally low K/Rb ratios. Moreover, the nature and mode of intrusion of late stage water-rich melts (assuming they give rise to pegmatites and aplites) as veins and dykes is at variance with the vitroclastic groundmasses of the porphyroids indicative of transport in a fluidized condition. It has already been pointed out (Chapter 5) that the porphyroids calc-alkaline and do not contain excess alkalies as corundum is present in the normative mineralogy.

2). Mode of Eruption.

There appears to be no evidence to suggest that the conditions attendant upon eruption of rhyolite magma significa alter the chemical composition of the resulting rocks in such manner that they deviate from the composition of residual liqu in the granite system. Hence, Ewart et al., (1968 a) have demonstrated that there is little difference in composition among the rhyolitic eruptive types - lava, ignimbrite and pumi in the Taupo region.

Taylor, et al., (1968) suggest that it is unlikely that partial loss of a fluid or gas phase during eruption of pyroclastic rocks will affect the $Na/_K$ ratio (nor the trace elemen ratios).

3). Secondary processes.

The importance of secondary processes in altering the composition of acid volcanics after extrusion has been emphasi by various workers. Processes considered to be significant in respect are late stage (deuteric) alteration, hydrothermal alteration and weathering (Scott, 1966 and Radulescu, 1966), groundwater leaching (Lipman, 1966) and devitrification (Noble 1965).

An inverse relationship between potash and soda shown to characteristic of most of the quartz-feldspar porphyroids stud (with the exception of Warrego Group B rocks) is recorded in rhyolitic ash-flows in Nevada (Scott, 1966 and Lipman, 1965 and 1966), and, according to Battey (1955), is typical of many geologically ancient rhyolitic volcanics such as late Palaeozo keratophyres of New Zealand and the Ordovician rhyolites of Great Britain.

This reciprocal relationship (in the Group A samples) between K_2O and Na_2O at reasonably constant total alkalies all a spread in composition of the porphyroids along the quartz-feldspar boundary in the granite system Q - Or - Ab - H_2O (Fig 19). This is consistent with replacement of one alkali by the other and dispersal of the compositions (apart from the Black Eye samples) along the quartz-feldspar boundary on either side of the residual liquid composition at the thermal minimum acco ing to whether potassium or sodium is replaced. Pseudomorphs of plagioclase after potassium feldspar megacrysts are present in the sodium-rich porphyroids consistent with replacement. The megacrysts of the potash-rich porphyroids are not replaced and these rocks owe their enrichment in potassium to their groundmass compositions (Fig. 20) which are too fine-grained to reveal any pseudomorphous textures. In terms of normative quartz, potassium feldspar and albite, the bulk compositions of the Black Eye Porphyroids which plot in proximity to the thermal minima at low water vapour pressures are considered to be virtually original and unaltered although the groundmasses may be slightly enriched in SiO_2 (Fig. 20).

Hence, there is evidence for replacement of sodium by potassium in four of the five analysed Warrego (Group A) speci The fact that the fifth sample (specimen 94) shows replacement of potassium by sodium (in terms of the pseudomorphous feldspa relationships which have also been seen in the petrography of other samples) allows the suggestion that internal redistribut of alkalies may have occurred in the porphyroidal body presuma through the agency of late stage aqueous or hydrothermal solut

In the case of the Creek Bed Porphyroid, the compositions of both analysed specimens indicate replacement of potassium by sodium and this is confirmed (via K-feldspars wholly or partially pseudomorphed by albite) in all specimens examined petrographically. However, the whereabouts of the replaced potassium remains unknown.

The adjacent granophyre (specimen 615, Table 18, Chapter is also sodium-rich as a result of the replacement of K-feldsp by albite (replacement being subsequent to the formation of th micrographic intergrowths).

The fact that both the porphyroid and the later granophyr are affected suggests that sodium enrichment occurred as one event and was presumably caused by late stage hydrothermal activity associated with the granophyre.

Scott (1966), in an account of compositional variations i ignimbrites, affirms the difficulty of attributing a secondary compositional change uniquely to a particular alteration proce However, he ascribes ion exchange between K and Na, while ment ing that Orville (1963) has demonstrated this experimentally between an aqueous phase and alkali feldspar, to either deuter or hydrothermal alteration.

With regard to the Group B samples, the bulk compositions of two specimens (12 and 35) are almost identical to those of the Black Eye Porphyroid except for very low soda values in th former. Hence their position in Fig. 19 may be explained in the main, by sodium leaching as may their high normative corundum content.

Ionic leaching, as opposed to ionic replacement, of alkal and silica is attributed to the action of ground water by Lipm (1966) and to weathering processes by Scott (1966).

The position of specimen 249 in the Or apex of Fig. 19 requires massive enrichment in potassium (magnesia is also hig which is expressed petrographically by the replacement of quar by biotite which is itself mainly altered to chlorite.

Scott (1966) and Radulescu (1966) feature compositions ha

9% and 12% K_2O (c.f. Warrego specimen 249) as being due to the action of hydrothermal and endogenic solutions respectively on acid volcanic rocks.

Low calcium values (as found in most of the porphyroids) characteristic of many of the acid volcanics described, and regarded as altered, by Battey (1955), Radulescu (1966), Terzaghi (1948) and Donnelly (1966) and tend to be associated with variability in alkali ratios. Scott (1966) documents the alteration of plagioclase by removal of Ca and its subsequent fixation, often elsewhere, as calcite and Ca - montmorillonite Leaching processes of this nature may be responsible for the very low calcium content of the porphyroids (and indeed of the associated volcanic greywackes and ashes).

It has been shown that the present compositions of the quartz-feldspar porphyroids are best explained by derivation from an original magmatic composition (most closely represent by the Black Eye samples) as a consequence of secondary proces resulting in the redistribution of K, Na and Ca as summarized in Table 14 (a). Compositional variations of this nature whicl have been recorded in volcanic rocks as mentioned above, are m commonly explained as being due to late-stage hydrothermal activity and, in accordance, it is suggested that this post magmatic, secondary process is responsible for most, if not al compositional variations of the quartz-feldspar porphyroids.

Estimation of water pressures prevailing during different tion and crystallization of ash-flow magmas appears possible (Lipman, 1966) by precisely relating the groundmass compositio of these rocks to the synthetic granite system Q - Or - Ab - H of Tuttle and Bowen (1958). However, in any case where second ary alteration makes rigid definitions of the original compositions impossible, the method has no realistic value. This applies to the two Black Eye samples as their present groundma compositions which plot in the quartz field (Fig.20) can only be approximate to their original magmatic compositions. This results because the groundmass compositions were calculated fr the megacryst and bulk rock compositions, the megacrysts including K-feldspar and plagioclase whose compositions appear have been somewhat modified from their original magmatic chara Also the possibility of minor adjustment of the bulk rock comp sitions by the secondary alteration which has affected all the other porphyroidal samples, cannot be ruled out.

Similarly, the secondary alterations makes it impossible to accurately relate the bulk rock compositions to the quinary system Or - Ab - An - SiO_2 - H_2O (as proposed by Carmichael, 1963) to compare the observed megacryst phases with the predic ones and to define a probable crystallization sequence for the mineral grains. From the resorption textures characteristic of the potassium feldspar and quartz megacrysts, it is assumed during the corrosion (testifying to changing physical conditic attendant upon movement of the magma into higher crustel level the bulk composition of the rocks plotted (on projection) in the plagioclase field of the Or - Ab - SiO_2 plane where only plagioclase was stable.

Associated Rocks.

Despite the fact that microscopic studies of the volcanic ashes indicate that they are composed wholly of former glass fragments, their compositions are far removed from the compositions of acid igneous rocks, certainly from calc-alkaline rhyolites. However, in composition, the ashes (specimens 247, 105 and 106, Table 12) are closest to two of the Warrego Group B Porphyroids (specimens 12 and 35, Table 10), having higher Al_2O_3 and total iron and magnesium and lower SiO_2 than the lat Hence, the low Na_2O and CaO contents of the ashes (and greywac may be explained in terms of the leaching processes mentioned above, perhaps with the low SiO_2 content of the ashes indicati more severe leaching due to a higher porosity (Lipman, 1965) i these rocks relative to the quartz-feldspar porphyroids. The reason for the higher amount of total iron and magnesium remai obscure, but the proximity of the volcanic ashes (and greywack to the Warrego ore body may make these rocks susceptible to wall-rock alteration phenomena.

The present compositions of the volcanic ashes are diffic to explain and may be a result of secondary processes operatin on rocks of rhyolitic composition. However, there seems no reason why the initial composition of the volcanic ashes could not have been more basic, such as rhyodacitic or dacitic.

It is also possible that if these rocks are reworked pyroclastics, they could have been mechanically fractionated during the reworking process with modification of their bulk compositions.

SOME TRACE ELEMENT RELATIONSHIPS.

The overall ranges of the trace element abundances for th quartz-feldspar porphyroids are summarized in Table 19 from data contained in Table 11.

Rubidium.

As indicated, the rubidium contents of the quartz-feldspar porphyroids range from 57 to 534 p.p.m. in direct sympathy wit the variable potassium content. The Black Eye rocks, whose alkali ratios are considered to be close to the original unaltered value, have an average of 211 p.p.m. which is just greater than the average value (170 p.p.m.) of low Ca granites (Turekian and Wedepohl, 1961).

Strontium.

Most of the strontium concentrations fall between 55 and 74 p.p.m. which is generally lower than the average value (100 p.p.m.) of the low Ca - granites but is not unusual for granitic rocks (Hall, 1967b). Sr values in the range 100 to 250 p.p.m. are found in the samples with the higher calcium concentrations.

Barium.

The barium abundances are generally within the range of 610 to 1243 p.p.m. which straddles the average barium value (840 p.p.m.) of the low Ca - granites.

Thorium - Uranium.

Only a few values of the $^{Th}/U$ ratio are available, those of the least altered Black Eye specimens being 3.9 and 6.5 whi is in the range (4 or above) considered typical for granitic rocks (Heier and Brooks, 1966).

Potassium - Rubidium.

The $^{K}/Rb$ ratios appropriate to the porphyroids are reproduced graphically in Fig. 21 for comparison with those of othe rocks. Despite the wide range in alkali ratios present in the porphyroids, only one of the more altered representatives (specimen 94) shows marked enrichment in rubidium. Most of th $^{K}/Rb$ values are in the range 174 to 224, which is close to the average value of about 220 for the continental crust (Kolbe an Taylor, 1966b) and hence indicate that the quartz-feldspar porphyroids are comparable to little-fractionated rhyolites suc as those of the Taupo region, New Zealand ($^{K}/Rb$ averaging 250, Ewart, et. al., 1968 a and b) rather than those displaying abnormal enrichment in rubidium such as the varieties from Ban Peninsula, New Zealand ($^{K}/Rb$ averaging about 100, Taylor et. a 1956) where the strong fractionation may result from magmatic differentiation.

Figure 21.

Potassium-rubidium relationships in some rocks and potassium feldspars at Tennant Creek.

- in the porphyroidal plots

. represents Warrego Group A samples

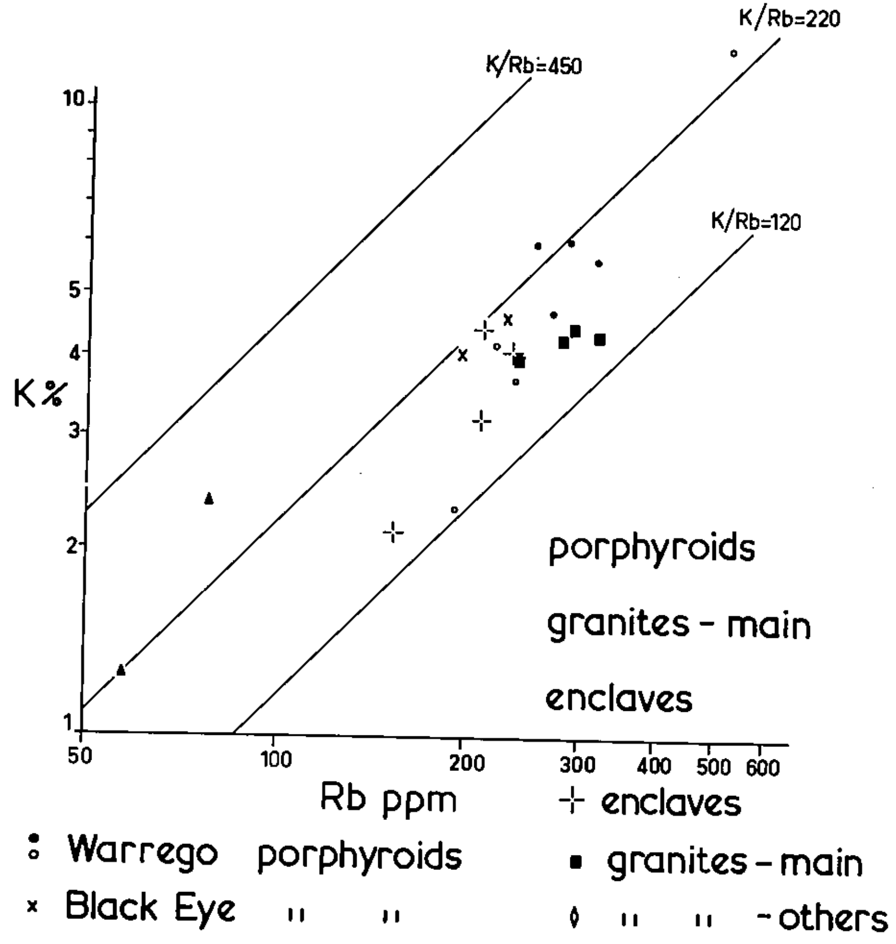
o represents Warrego Group B samples

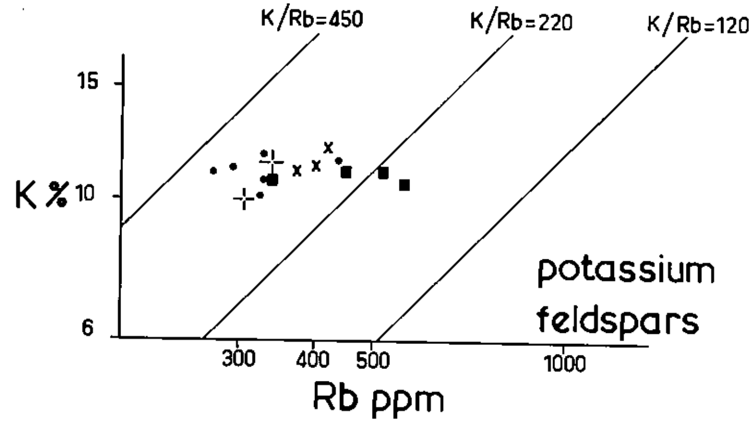
- in the granite plots

main granites - phase A

others - phases B and C

K - Rb relationships in some rocks and feldspars from Tennant Creek





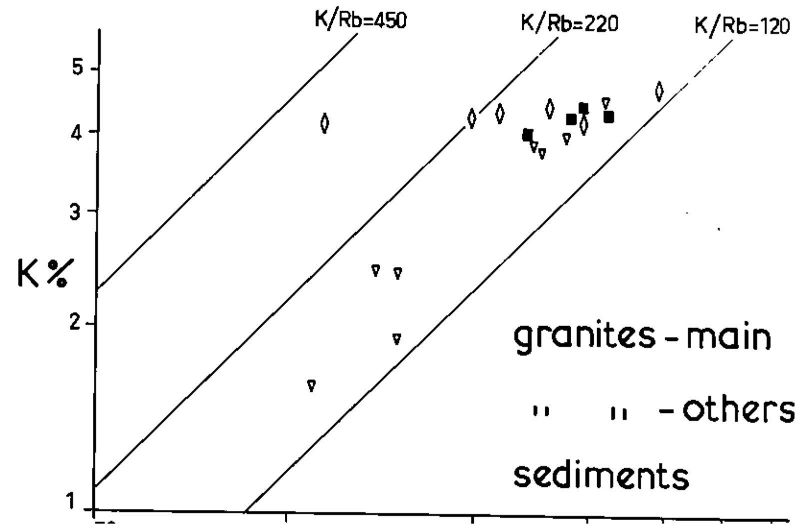


TABLE 19.

Range of some trace element values in Tennant Creek rocks.

ROCK TYPES	Rb	Sr	Ba	Th	U
Porphyroids	57-534	4-243	416-2026	16-35	0-7
Granites	13-393	63-549	132-924	11-38	0-14
Enclaves	151-236	55-96	616-987	-	-
Volcanic Ashes	249-328	2-18	587-751	13-35	0-30
Volcanic greywackes	140,150	0,3	310,311	8,19	0,10

All values in p.p.m.

The quartz-feldspar porphyroids are less fractionated tha the main (phase A) granites of the Station Hill area in terms of the $^{K}/Rb$ ratio (Fig.21). This is also the case with the ratios $^{Ba}/Rb$, $^{Ba}/Sr$, $^{Ba}/K$ and $^{Sr}/Ca$ (Table 11) all of which, as pointed out by White (1966), generally decrease as a result of fractionation processes.

The $^{K}/Rb$ ratios of the volcanic ashes and greywackes are generally low at 138 to 155 and 161 to 176 respectively.

COMPOSITIONAL FEATURES OF THE FELDSPARS AND THEIR SIGNIFICANCE.

Major Element Content.

In summary, the compositional variations in the potassium feldspar megacrysts are compared diagrammatically in Fig. 22 using data recorded in Table 4.

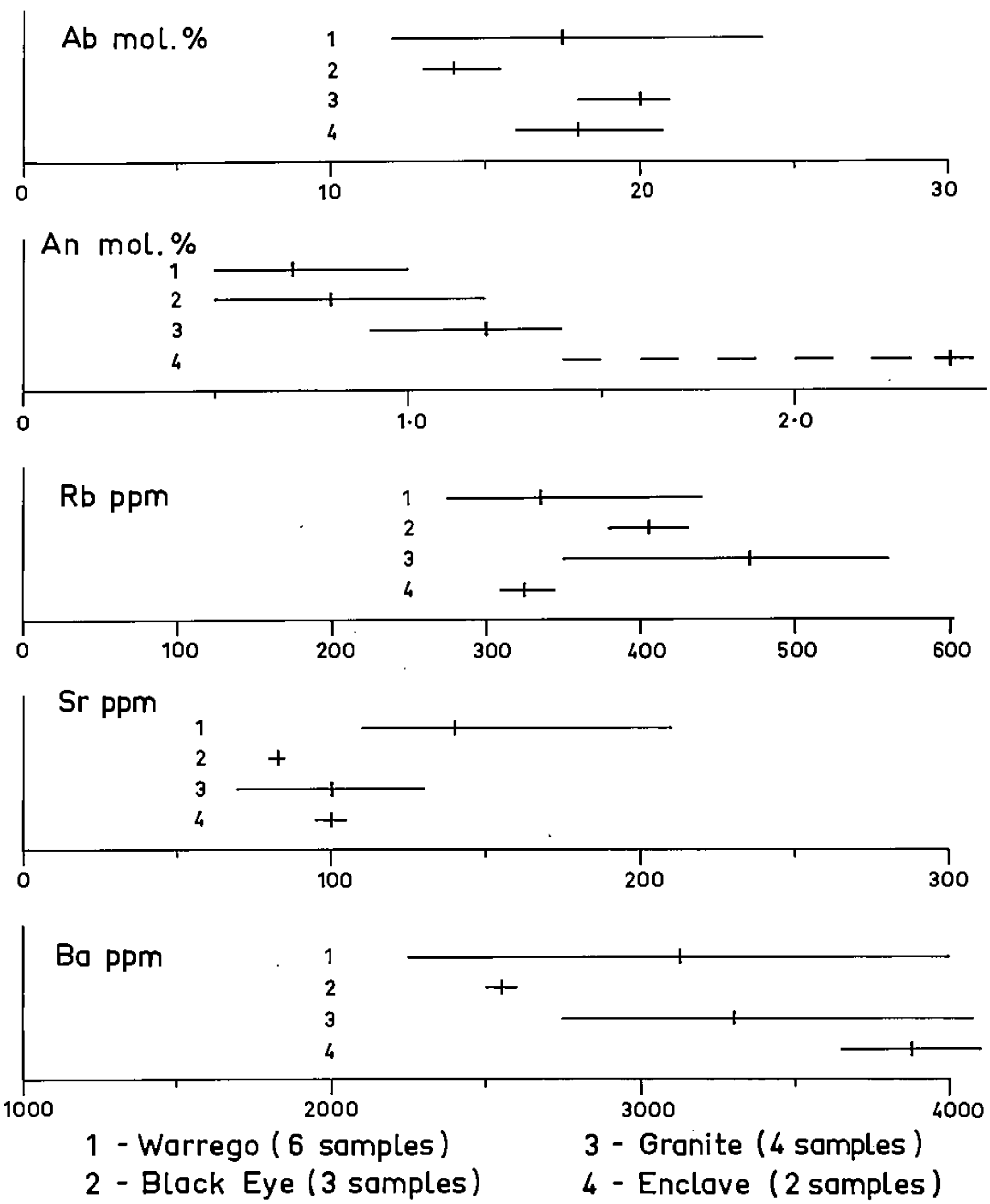
In albite content, the K-feldspars of the Warrego Porphyr show most variability, ranging from 12 to 24 mol. % with an average at 17½ mol. % while those of the Black Eye Porphyroid are relatively constant at 13 to 16 mol. %. The K-feldspar of the Creek Bed Porphyroid is not included here because of the widespread replacement of that feldspar by albite (one megacry measured by X-ray diffraction methods gave a composition of 33 mol. % Ab + An which is certainly due to replacement effects).

The anorthite content shows little variability, all value falling within the range 0.5 to 1.2 mol.

As indicated in Tables 5, 6 and 9, the compositions of th

Figure 22.

Compositional variations in potassium feldspars from porphyroidal and granitic rocks at Tennant Creek.



Compositional variations in potassiu
feldspars from porphyroidal and
granitic rocks

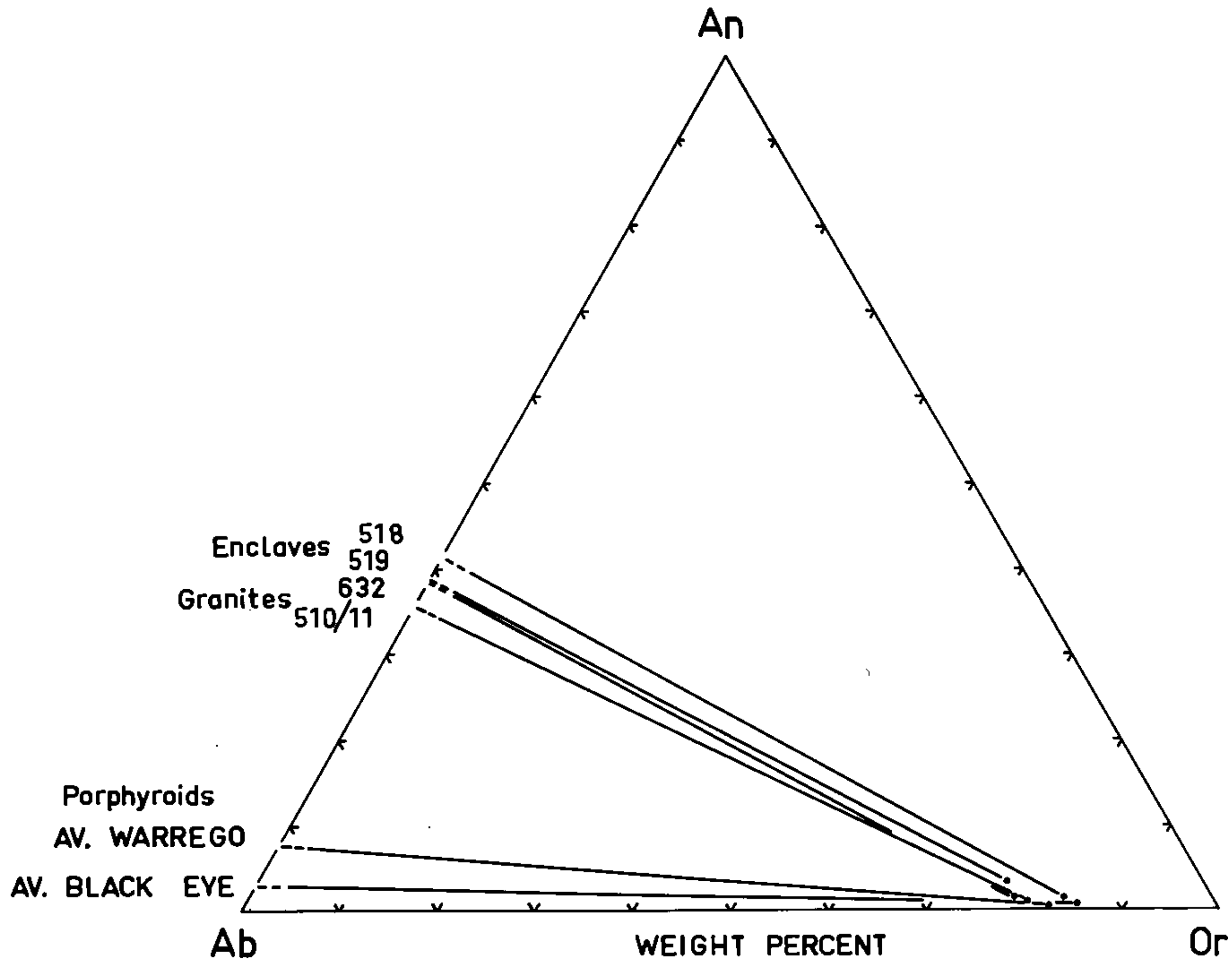
plagioclase megacrysts were determined optically as albite (An_{2-9}) in all of the porphyroids except for some of the Warre rocks which also contain andesine (An_{38-41}).

The compositions of the feldspars occurring in the Warreg and Black Eye Porphyroids are plotted in Fig. 23 in terms of Or, Ab and An and are joined by tie-lines. Only the averaged compositions (six Warrego and three Black Eye samples) are featured in the diagram and adequately represent the compositi al pattern of the feldspars in these rocks (except for the few andesines found in some of the Warrego rocks). The plagio clase compositions are not represented by points as their Or content was not determined.

From the results of work in the system Or - Ab - An - H_2O at 5 K. bars water pressure, Yoder et al. (1957) deduced that tie-lines joining coexisting feldspars in igneous rocks are more nearly parallel to the Or - An than the O r - Ab sideline at the relatively high temperatures and low pressures associat with crystallization and equilibrium in volcanic environments when compared with plutonic conditions. Volcanics may reasona be expected to show evidence of higher temperatures in their mineralogy when compared to plutonic rocks, whether this be du to higher actual crystallization or equilibrium temperatures o more complete preservation of similar initial chemical pattern

Figure 23.

The compositional pattern in terms of Or-Ab-An of coexisting feldspars in some Tennant Creek rocks.



Co-existing feldspars in some Tennant Creek rocks in the volcanics due to their more rapid cooling.

The orientation of the tie-lines of the porphyroidal feld spars along the Or - Ab sideline in Fig. 23 is then at varianc with the pattern attributed by Yoder et al. (1957) to the feld spars existing as primary phases in volcanic rocks.

Inspection of Fig. 23 reveals that the orientation of the feldspar tie-lines is controlled to a large extent by the plagioclase composition, hence any change in composition of th plagioclase will produce a marked change in orientation of the tie-lines.

Further experimental results suggest that it is unlikely that feldspars having compositions similar to the K-feldspars and albite in the porphyroids could have crystallized from a silicate melt (Tuttle and Bowen, 1958, p.138). Also Piwinskii (1968a) records coexisting feldspar compositions, similar to those of the porphyroids investigated in this study (Fig. 23), in the subsolidus stage of experimental melting relations conducted on natural granitic material at a water pressure of 2 K bars.

Hence, experimental information indicates that the plagioclase megacrysts in the porphyroids are unlikely to have formed with their present composition as a result of magmatic processe However, as already indicated, textural aspects relating to gra shape and twinning suggest a magmatic origin for the feldspars which infers in turn that the porphyroidal plagioclases were originally more calcium-rich and were altered to albite subse-quent to magmatic crystallization.

Also, petrographical studies indicate that most unaltered calc-alkaline rhyolites have oligoclase or andesine as their plagioclase phase (Larsen, et al. 1938, Donnelly 1963, Lipman 1966, Noble 1966 and Scott 1966). The existence of andesine grains in some parts and "dusty" albite grains in other parts of a few of the Warrego rocks (e.g. specimens 93 and 94) suggests that the albite grains have altered from the andesine grains which have clear surfaces and traces of oscillatory zoning.

The absence of saussurite in the albite grains or of any identifiable calcium-bearing minerals in the groundmass, is consistent with the low value of CaO in the rock compositions and infers that some calcium has been removed.

Anorthite-bearing plagioclase is unstable when undergoing greenschist facies metamorphism or hydrothermal alteration (Noble, 1966) and alters to albite which may still preserve its original twinning and grain shapes (Eisinger et al., 1962). This feature of the porphyroidal albites has already been mentioned.

The fact that the calcium has apparently left the rock suggests that hydrothermal alteration has been responsible for the albitization rather than low grade metamorphism which would be expected to preserve the calcium as saussurite or other calcium-bearing minerals (Scott, 1966; Noble, 1966). The variability of the alkali content of the rocks is also consist with hydrothermal alteration. No calcium-bearing alteration products have been identified in the porphyroids but at least some of the calcium may be retained in the occasional veinlets of calcite which are present in the rocks.

The foregoing evidence indicates that the porphyroidal plagioclases have been originally andesine and similar in composition to the plagioclase present in the granite and enclaves which do not appear to have altered from their origin magmatic condition, as their delicate, oscillatory zoning is preserved.

It has already been mentioned that from the experimental data of Tuttle and Bowen (1958, Fig. 11), the K-feldspar of th porphyroids have albite contents which infer minimum temperatu of formation of approximately 400 to 500° C.

The distribution of sodium between coexisting potassium feldspar and plagioclase in equilibrium can also be used as a geothermometer (Barth, 1956, 1961, 1962 and 1968) and k-values are considered to become larger primarily as a function of increasing temperature where

$$k_{(T,\ P)} = \frac{\text{mol.fraction of Ab in K-feldspar}}{\text{mol.fraction of Ab in plagioclase}}$$

On this basis, the present sodium content of the porphyroidal feldspars indicates temperatures of between 400 and 53[illegible] (Table 20). However, estimation of temperature has little significance in this case because of the evidence for modifica- tion of the plagioclase compositions.

Treating the original plagioclase composition as andesine gives a feldspar assemblage in the porphyroids similar to that present in the main (phase A) granite and enclaves which according to the geothermometer has a temperature of formation in the range 540 to 600^{o} C. These temperatures are considered to be just below magmatic values appropriate to melts of grani composition (Barth, 1956; Tuttle and Bowen, 1958 and Kleeman, 1965). This implies either that the K-feldspars lost some sodium due to postmagmatic (Hall, 1967a and Mehnert, 1968) or metamorphic recrystallization, or that there are inaccuracies the geothermometer, which has been criticized on various groun by several workers (Dietrich, 1962; Winkler, 1961; Piwinskii, 1968 a and b and Virgo, 1969).

In conclusion, it appears that the major element patterns now present in the feldspars of the porphyroids are not origin and have been produced by post-consolidation processes. The albite composition of the plagioclase is considered to be due hydrothermal alteration and the potassium feldspar composition be the result of either hydrothermal alteration or metamorphic recrystallization or a combination of both.

TABLE 20.

Sodium content of coexisting feldspars in porphyroids and granites.

Specimen	Ab (mol.%) in pot.feldspar	Ab (mol.%) in in plag.	$k_{(T,P)}$	Temp. °C
Warrego Porphyroid (Range)	12-24	91-96	0.13-0.26	400-535 *
Black Eye Porphyroid (Range)	13-16	96-98	0.13-0.17	400-450 *
Station Hill Granite (phase A)				
632	21	63	0.33	600
510/11	20	66	0.30	570
Enclaves in granite				
518	16	60	0.27	540
519	21	63	0.33	600

$$k_{(T,P)} = \frac{\text{mol. fraction of Ab in potassium feldspar}}{\text{mol. fraction of Ab in plagioclase}}$$

after Barth (1956).

* According to Barth (1968), no plagioclases more albitic than An 25 may be utilised with confidence to estimate exact temperatures less than 500° C. because of the peristerite gap.

Trace Elements.

The rubidium, strontium and barium contents of the porphyroidal potassium feldspars (six Warrego and three Black Eye samples) have the ranges 279 to 439 p.p.m., 79 to 210 p.p.m. and 2262 to 4006 p.p.m. and are illustrated diagrammatically i Fig. 22. All values are within the wide ranges reported by Rhodes (1969) for these elements in potassium feldspars from granitic rocks.

The same element ratios used to investigate possible fractionation trends in the rocks were calculated for their potassium feldspars (Table 21). All of them, with the excepti of $^{Ba}/Sr$ and $^{Ba}/K$, generally reflect the relationship already found in the bulk rock data that the average ratios for the granite K-feldspars are slightly smaller (the ranges often overlap) than those of the feldspars from the Warrego and Blacl Eye Porphyroids.

In comparing element ratios between a rock and a single constituent mineral species, it should be kept in mind that modal variations of other minerals in the rock may influence the ratios in the mineral being considered (Kolbe and Taylor, 1966a).

The potassium-rubidium ratios for the porphyroidal potassi feldspars (263 to 401) are diagrammatically reproduced in Fig. (along with the K-feldspars from all environments) where they plot within the limits considered by Heier and Taylor (1959) to

TABLE 21.

Potassium Feldspar Megacrysts - Selected Element Ratios.

	K/Rb	Ba/Rb	Ba/Sr	Rb/Sr	Ba/K.10^3	Sr/Ca
WARREGO						
2	347	11.1	17.8	1.6	32	210
5	374	10.3	22.9	2.2	28	104
51	323	6.8	18.9	2.8	21	133
61	308	7.5	21.8	2.9	25	114
62	401	14.4	28.0	2.0	36	110
401	263	7.2	29.5	4.1	28	154
Av.	336	9.6	23.2	2.6	28	138
BLACK EYE						
479	279	6.4	31.2	4.9	23	49
480	282	6.1	32.7	5.4	21	113
477	289	6.5	29.5	4.5	23	106
Av.	283	6.3	31.1	4.9	22	89
CREEK BED						
*606	306	4.8	2.1	0.4	16	20
GRANITE						
G	189	4.9	39.8	8.1	26	38
510/11	214	5.6	37.0	6.6	26	49
632	312	10.0	26.1	2.6	32	67
621	245	8.9	35.1	3.9	36	83
Av	240	7.4	34.5	5.3	30	59
ENCLAVE						
518	327	12.0	42.9	3.6	37	48
519	325	11.9	35.2	3.0	37	23
Av.	326	12.0	39.1	3.3	37	35

* plagioclase

be normal. When used in conjunction with the $^{Ba}/Rb$ ratio which Taylor and Heier (1960) claim to be a more sensitive indicator of fractionation, the $^{K}/Rb$ ratios of the feldspars are seen in Fig. 23 to increase in sympathy with the former ratio. In the same diagram, the rubidium-strontium relationships are featured and tend to have an antipathetic character.

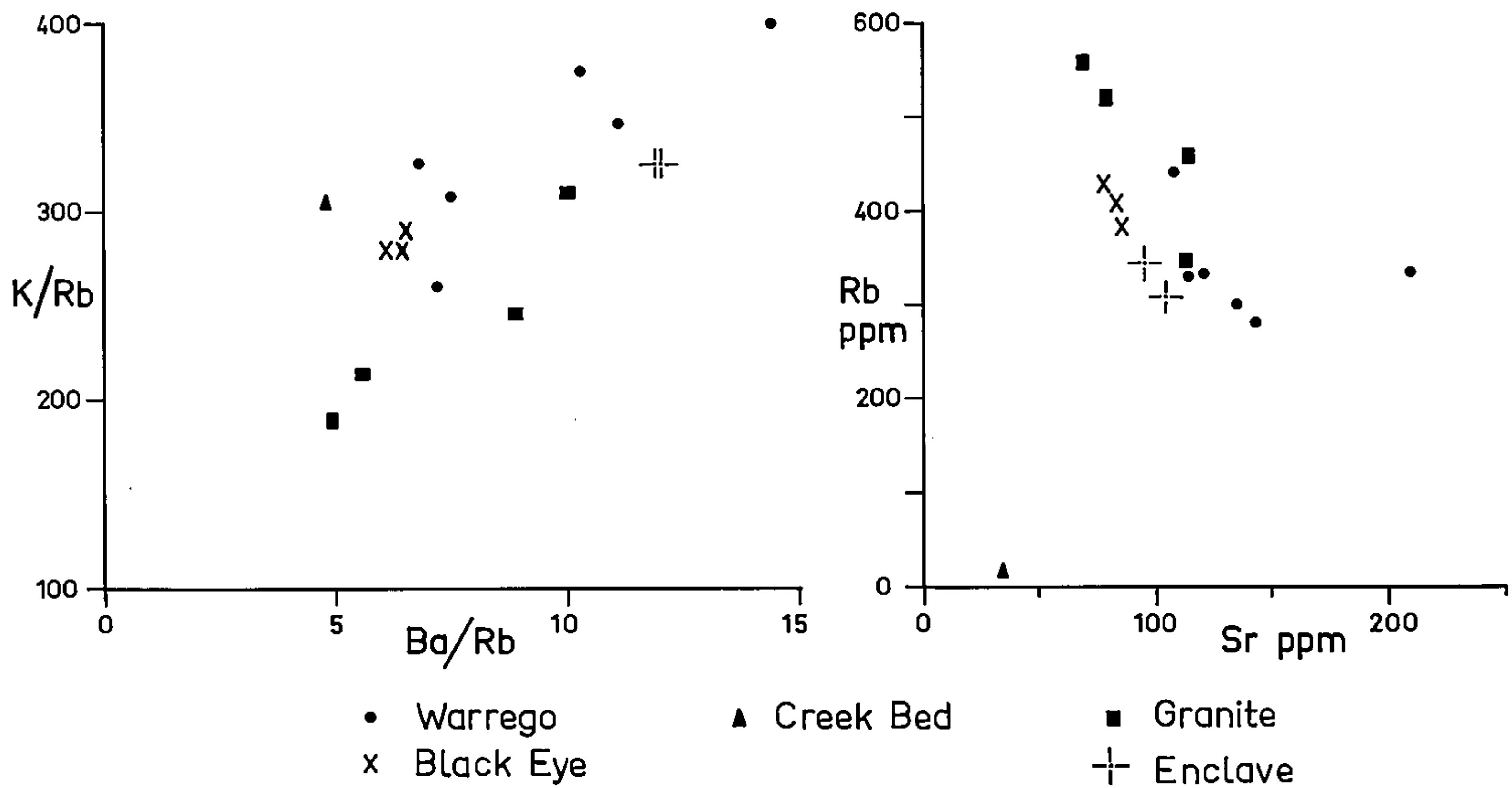
Hence, on the basis of these ratios, the feldspars from th different rock types do not clearly fall into distinct groups, but have a trend in which the porphyroidal potassium feldspars appear slightly less fractionated than those of the main (phase granite.

The strontium contents (20 to 110 p.p.m.) of the albite megacrysts of the porphyroids are not unusual for plagioclase o that composition. The barium abundances (150 to 480 p.p.m.), however, are more typical of oligoclase or andesine composition rather than albite which generally have Ba concentrations of less than 100 p.p.m. (Heier, 1962). The albite replacing the K-feldspar megacrysts in the Creek Bed Porphyroid appear to hav appropriately low concentrations of Rb, Sr and Ba being 16, 36 and 77 p.p.m. respectively. No data are available on the concen- trations present in the relict andesine megacrysts recorded in t Warrego Porphyroid.

The relatively high barium content in the albite megacrys

Figure 23 (a).

Selected trace element relationships in potassium feldspars in some Tennant Creek rocks.



Trace element relationships in potassium feldspars ise difficult to explain as the structure of albite would appea to be unfavourable and would tend to reject Ba (Heier, 1962). may be that, when the original plagioclase (andesine?) was alte to albite, the Ba concentrations appropriate to the original compositions were, for some reason, retained.

The possibility of using trace element distribution ratios between coexisting feldspars as geothermometers has been discus: by Barth (1961) and Heier (1962). According to the latter, elements partitioning between two phases may be expected to app: more closely the "dilute solution" requirements of the Nernst d: tribution law providing they are present in the form of trace, rather than major, constituents. Partly on account of their ionic properties (the crystal structure of the incorporating mineral is also important), Rb and Ba have far greater tendencie to substitute in the potassium feldspar lattice rather than in the plagioclase structure, while Sr appears to be accepted by both feldspar lattices with approximately equal ease.

The recent work of Virgo (1968) concerning trace element partition between feldspars in high grade metamorphic rocks has confirmed that, compared to Ba and Rb, Sr is the most promising element for geothermometry. Drawing from both empirical and exp mental data, Virgo has ruled out compositional and pressure effe and has concluded that the distribution of Sr between coexisting feldspars is predominantly temperature dependent with potassium feldspar preferentially accepting Sr with increasing temperatur

As indicated by Hall (1967 a), strontium substitutes in th feldspar lattice more readily for K and Ca than for Na and that although the sodium content of the K-feldspar at the time of crystallization may be reduced by post-magmatic recrystallizati the original strontium content may be preserved, making Sr a potentially valuable indicator of the crystallization temperatu of the feldspars.

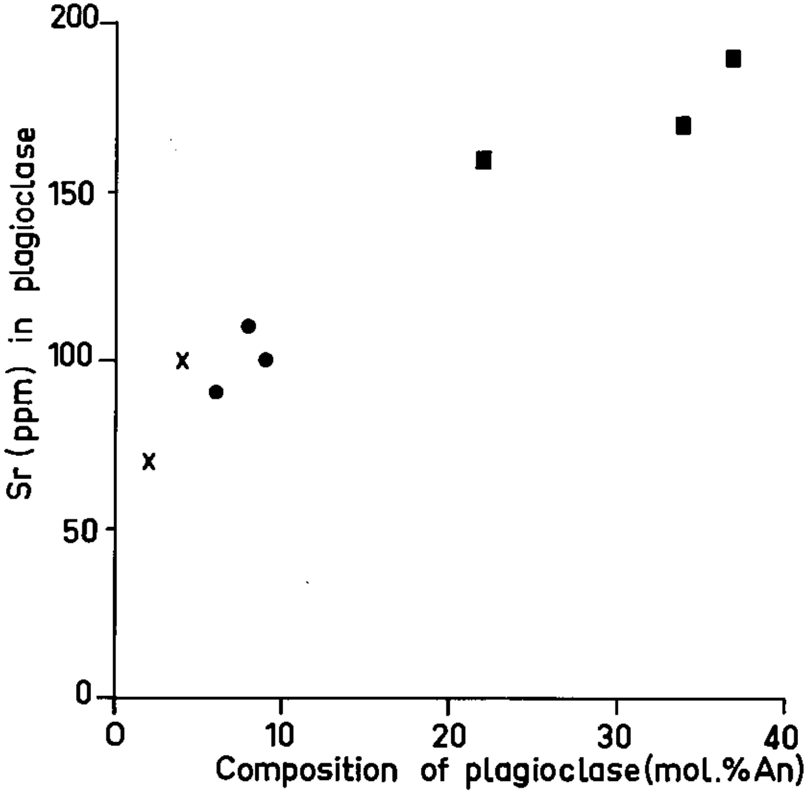
In potassium feldspar and plagioclase occurring together i the porphyroidal and granitic rocks, the Ba concentration is heavily biased towards the potassium feldspar phase as found by Heier (1962). There is little distinction between the porphyroi and granitic feldspars with respect to barium.

The Sr contents, illustrated graphically in Fig. 24, appea to reveal a systematic difference between the porphyroidal and granitic feldspars (bearing in mind the relatively few plots available). Comparing the Sr content of the plagioclases, the porphyroidal albites have less than the granitic andesines which consistent with the relationship of decreasing Sr with decreasin An-content (Fig. 24) found in the plagioclase of acid rocks (Hal 1967 a). Whereas the Sr concentration is roughly equal in both feldspar phases from the Warrego and Black Eye Porphyroids, the plagioclases in the granite are enriched in Sr relative to their accompanying potassium feldspars.

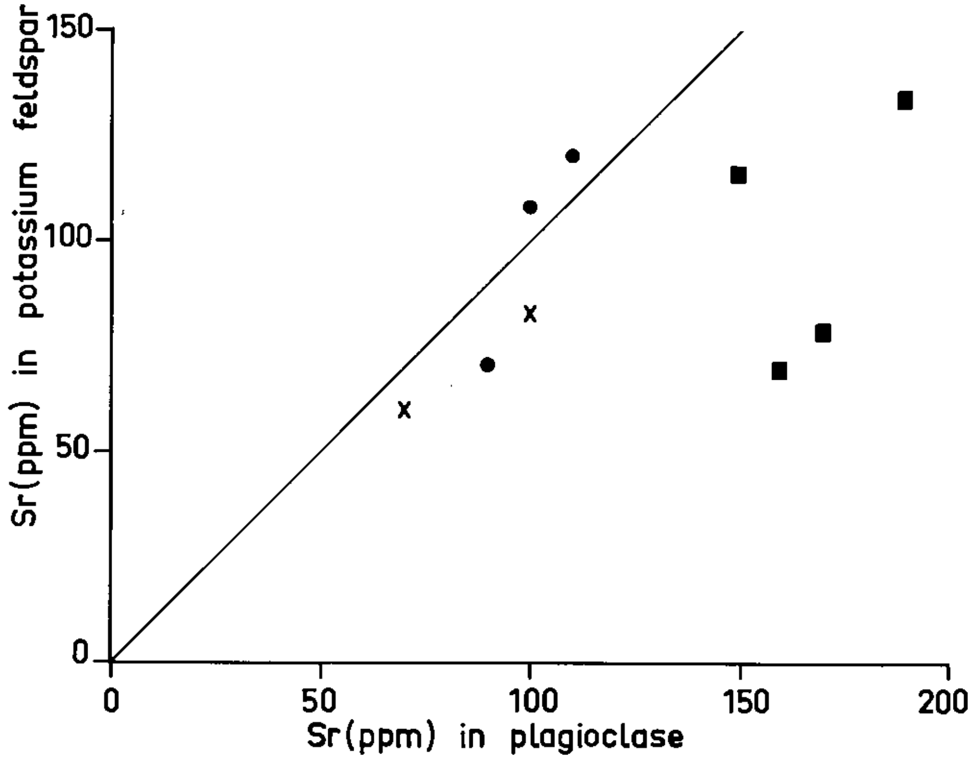
Figure 24.

The strontium content of coexisting feldspars in porphyroidal and granitic rocks at Tennant Creek.

Sr and anorthite contents of plagioclases from porphyroids and granites



Distribution of Sr between coexisting feldspars from porphyroids and granites



● Warrego porphyroids

The distribution pattern of Sr in the granite feldspars (F 24) is similar to that found by Hall (1967 a) in granites fr Donegal, Ireland in that more Sr is present in the plagioclas when compared with the potassium feldspar, As pointed out by Hall, this may infer that the feldspars crystallized at a tem perature below the minimum temperature at which Sr becomes pr ferentially accepted by K-feldspar. The higher gradients rec ded for the porphyroidal feldspars in Fig. 24 ($\simeq$I) are con sistent with a higher temperature of crystallization relative to the granite feldspars (gradient less than 1). However, as the albite of the porphyroids appears to have derived from andesine, it is possible that during the alteration some Sr would be lost along with the calcium due to the similar chemi behaviour of these two elements.

Hence, the distribution pattern preserved in the porphyroic feldspars could have originally been similar to that of the granite feldspars, the subsequent Sr loss moving the plots parallel to the plagioclase axis in Fig. 24 and increasing the gradient to its present value ($\simeq$I). Therefore, the alterat of plagioclase prohibits the confident use of strontium distri butions, as well as those of sodium, to estimate temperatures even on a relative basis.

STRUCTURAL STATE OF THE FELDSPARS.

Potassium Feldspar.

Information on the structural condition of the potassium feldspar megacrysts in the quartz-feldspar porphyroids is available from optical and X-ray measurements carried out as already outlined (Chapter 3).

The potassium feldspar megacrysts from the different roc types may be compared by plotting each composition (Or conten as recorded from X-ray measurements) against the average opti axial angle on the classification diagram (Fig. 25) of Tuttle (1952). These plots suggest that, whereas the K-feldspars sh little variation in potassium content expressed as weight per of the orthoclase molecule, there is a tendency for the porphyroidal K-feldspars to have lower optic axial angles (2Vx) than those present in the granite and enclave grains.

The average value of 2Vx for each K-feldspar megacryst plotted on histograms in Fig. 26, reveals that in the bulk av age for each rock-type, the porphyroidal potassium feldspars in fact have smaller optic angles than those of the feldspars in the granite and enclaves. Simple statistical tests (Appen II, Table VII) confirm that no difference of any significance exists between the Black Eye and Warrego Porphyroids and betw the granite and enclaves with respect to the optic angles of potassium feldspars. On the other hand, extremely significan differences are apparent between the porphyroid and the grani

Figure 25.

Potassium feldspar megacrysts from Tennant Creek rocks plotted on a modified version of Tuttle's (1952) classification diagram.

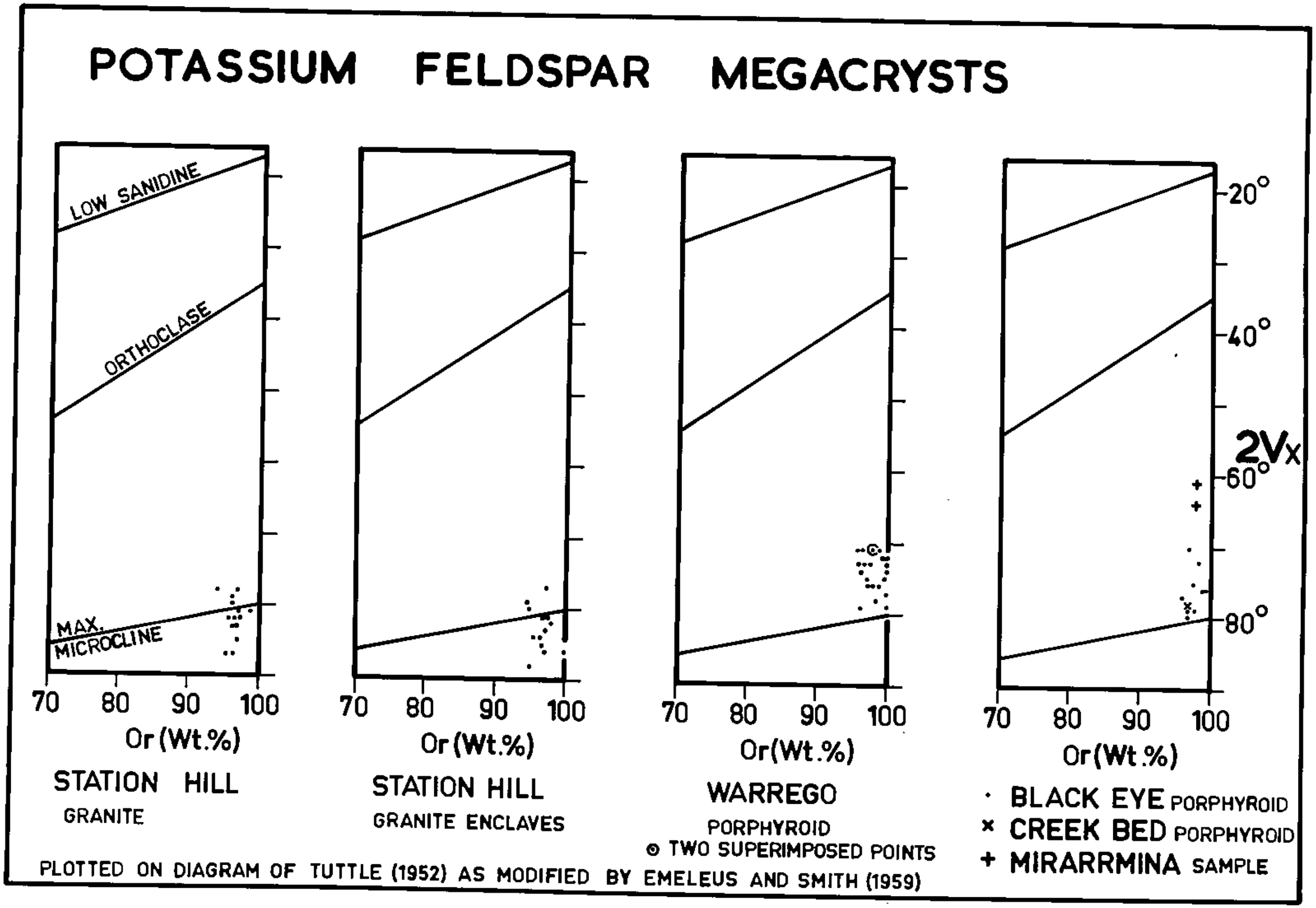
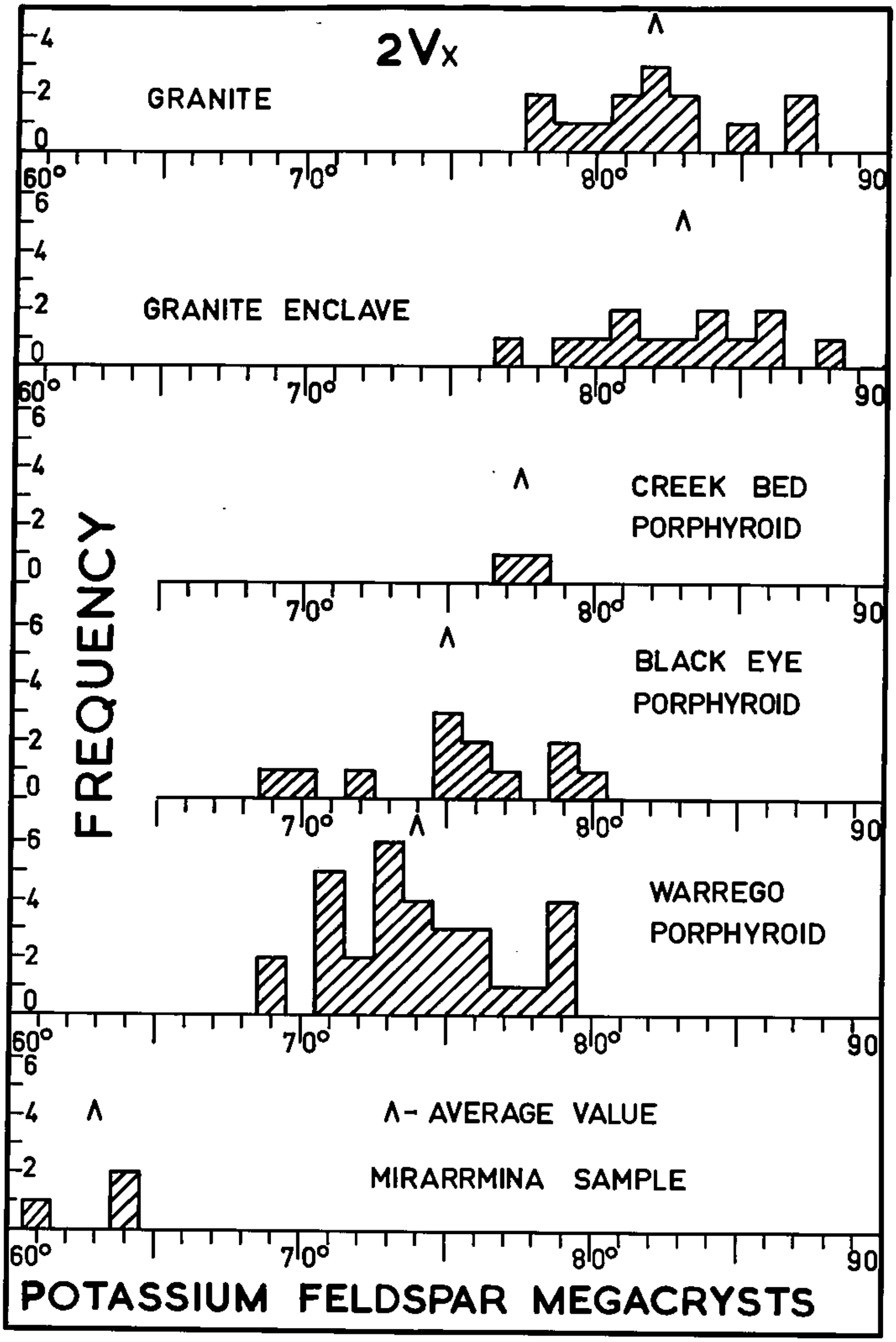

POTASSIUM FELDSPAR MEGACRYSTS
LOW SANIDINE
ORTHOCLASE
MAX. MICROCLINE
70
80
90
100
Or (Wt.%)
STATION HILL
GRANITE
STATION HILL
GRANITE ENCLAVES
WARREGO
PORPHYROID
⊙ TWO SUPERIMPOSED POINTS
20°
40°
60°
80°
2Vx
· BLACK EYE PORPHYROID
× CREEK BED PORPHYROID
+ MIRARRMINA SAMPLE
PLOTTED ON DIAGRAM OF TUTTLE (1952) AS MODIFIED BY EMELEUS AND SMITH (1959)

Figure 26,

Histograms of the average optic axial angle values (2Vx) of potassium feldspar megacrysts from Tennant Creek rocks (each plot consisting of an average of five determinations).



2Vx
GRANITE
GRANITE ENCLAVE
CREEK BED PORPHYROID
BLACK EYE PORPHYROID
WARREGO PORPHYROID
Λ- AVERAGE VALUE
MIRARRMINA SAMPLE
FREQUENCY
60°
70°
80°
90
POTASSIUM FELDSPAR MEGACRYSTS

values.

At constant composition, the value of the optic axial angle depends only on order-disorder relations in terms of Si - Al distribution (Marfunin, 1961). Hence the porphyroida K-feldspars with smaller optic angles than those from the granite and granite enclaves are slightly less-ordered than t latter.

Potassium feldspars from the granite, granite enclaves a the Black Eye Porphyroids consist of microcline with maximum obliquities (0.80 - 1.00). The narrow range in obliquity indicates an approach to equilibrium in the structural state the K-feldspars within the various environments. The Warrego Porphyroid, however, has a suite of potassium feldspars which possess a distinctly different pattern in their obliquities. Although, for convenience, the feldspars were listed accordin to their diffraction patterns, into Groups 1 and 3 separated by an intermediate Group 2 (Chapter 3), they may be considere as a reasonably continuous series ranging from the maximum mi clines similar to those of the other environments to the feld of Group 3, having mainly intermediate obliquities, by an inc in the proportion of coexisting material having zero or low obliquities.

The Group 3 feldspars do not generally have the broad, diffuse reflection in the $131/1\bar{3}1$ region reported by Virgo (1 for randomly-disordered feldspars (the term being applied by Christie (1962 b) to those feldspar grains having a complete range of obliquities). The size of the monoclinic peak may b smaller or larger than the associated triclinic peaks and, wh the former becomes dominant, the latter always appear as dist shoulders on the monoclinic peak. This suggests that the fel spars of Group 3 consist of material with only two distinct obliquities which are approximately zero and intermediate (N.I the Group 3 feldspars are mistakenly represented in Fig. 5 and Table 3 as if they were randomly-disordered).

The range of obliquities developed in the Warrego potassi feldspars is a disequilibrium feature and may be caused either variations in order-disorder relationships, or by variations i sub-X-ray twinning (Hafner and Laves, 1957). The fact that th average optic axial angle of the K-feldspars within each of th three groups is similar, may indicate that the order-disorder relations are similar, with the inference that the different obliquities may be related to a variable development of sub-X- twinning.

In a review of the structural states of potassium feldspa in differing geological environments, Dietrich (1962) indicate that the potassium feldspar should be monoclinic in volcanic associations unless there has been subsequent deformation anc metamorphism which promotes ordering to microcline. Hence th greenschist facies metamorphism experienced by the rocks at Tennant Creek could account for the existence of microcline i the quartz-feldspar porphyroids.

However, the variable development of a monocline peak in association with the triclinic peaks of intermediate microcli as found in the Warrego potassium feldspar (Group 3) X-ray patterns deserves further comment.

Bearing in mind the small number of samples recorded, th distribution of the feldspars having monoclinic peaks cannot apparently be simply related to their occurrence at particula positions in the Warrego Porphyroid. Of the eight K-feldspar samples comprising Group 3, one half occur at visible contact Neither are the Group 3 K-feldspars restricted to the least foliated rocks.

Potassium feldspars, having more than one obliquity withi individual grains, are reported from a number of different environments.

Randomly-disordered feldspars having a complete range of obliquities are found in augen gneisses and migmatites of the upper amphibolite facies (Smithson, 1962), in deformed orthoclase-bearing sub-volcanic granites (Rhodes, 1966) and also in rapakivi granites (Savolahti, 1962). The exact mode of format of these feldspars is not well known and pneumatolytic or hy thermal environments may be required (Christie, 1962 b) or a particular combination of growth rate, shear, temperature an volatiles (Smithson, 1962).

Feldspars having two distinct obliquities of a low or z and maximum or near-maximum nature, are reported in a number cases in natural environments in which microcline has been h by thermal metamorphism (e.g. Steiger and Hart, 1967; Wright, 1967; Tilling, 1968 and Rao, 1960, although gradational obliquities also occur in the latter case).

As there is no evidence of reheating in the Warrego area the pattern of structural states may have resulted during dis equilibrium cooling (c.f. Tilling, 1968). However, in the ev of the feldspars remaining monoclinic * after the cooling per (which is probable in volcanics according to Dietrich, 1962), the disequilibrium pattern may have been conferred either dur the secondary alteration processes for which there is evidenc the porphyroids or during the metamorphic conditions of the greenschist facies in which temperature is relatively low and shearing stress and water pressure (both of which are thought to promote ordering according to a review by Smithson, 1962) may vary from place to place.

* Whether the original monoclinic variety was sanidine or or clase remains unknown but the equant habits may indicate orth clase rather than sanidine.

Plagioclase.

Plagioclases from volcanic and subvolcanic environments generally have low-to intermediate-order structural states (w reference to Si - Al order) unless they have been subjected t metamorphism or alteration (Uruno, 1963: Noble, 1966 and Rhod 1966).

Both optical and X-ray measurements reveal that the plag clases in the porphyroids, as well as those in the granite an enclaves, irrespective of their textural type, have high-orde structural states typical of plagioclase from plutonic or met morphic environments.

This structural condition in the plagioclases of the por phyroids must have originated during hydrothermal alteration or greenschist facies metamorphism, or both. The two process appear capable of producing high-order structural states in initially-disordered plagioclases. Hence, albitisation of mo calcium-rich plagioclase is expected to remove any disorder p sent in the original plagioclase (Noble, 1966). Also, there are indications in the mineral assemblages present in the por phyroids that the regional metamorphism may have reached the grade of middle greenschist facies which, according to Noble (1966) are the minimum metamorphic conditions capable of orde plagioclase of a low- or intermediate-order structural state. The few andesine grains which escaped chemical alteration in Warrego Porphyroid have a high-order structural state, probab due to the greenschist facies metamorphism (as relict anorthi bearing plagioclase need not order under hydrothermal conditi Noble, 1966).

CHAPTER 9.

PETROGENESIS OF GRANITIC ROCKS AND THEIR BEARING ON THE ORIGIN OF THE QUARTZ-FELDSPAR PORPHYROIDS.

PETROGENESIS OF STATION HILL GRANITES.

Relation of compositions to the granite system.

All the granites contain approximately 80% or more of normative quartz + orthoclase + albite and hence qualify for comparison with the synthetic granite system determined by Tuttle and Bowen (1958).

The quartz and feldspar in the Barth mesonorms of the gr ites (Table 18), recalculated to weight percent (after Hall, are plotted on a projection of the experimental system Q - Or H_2O in Fig. 19.

The granites plot near the low-temperature trough on the quartz-feldspar phase boundary for 500 bars water-vapour pres except for the alumina-undersaturated specimen 616 which lies the vicinity of the boundary corresponding to 3 kilobars. Ni the eleven alumina-saturated granites occur in a close groupi just inside the quartz field and lying on the trend of the sul sidiary thermal valley defined by the locus of the thermal mi on the quartz-feldspar boundary for different water pressures

The close proximity of the rock compositions to the expe mentally determined minimum melting composition in the above system may be regarded as substantial evidence for a magmatic origin of the granites involving crystal-melt equilibria.

The two granophyres (specimens 615 and 609) have alkali ratios which cause them to occur near the Q - Ab edge of the triangular diagram. Their position is consistent with the textural evidence of replacement of potassium by sodium at constant quartz content which ensures that they are displaced from the thermal minima along a line parallel to the Ab - Or base of the diagram.

Since the original work of Tuttle and Bowen (1958), more information is now available on the behaviour of the granite system with anorthite as an additional component.

In terms of the estimate of White, et. al.,(1967), using the data of von Platen (1965) that "for every one per cent increase in normative anorthite, the quartz content of the mi mum increases by about one per cent", the main granites (phas of the complex may have formed at 1,500 to 2,500 bars water-vapour pressure and the subsidiary members at 500 to 2,000 ba assuming the magma was saturated with water.

Reference of the granite compositions to the system Or - An - SiO_2 - H_2O discussed by Kleeman (1965) reveals that most the rocks plot in the relatively narrow low-temperature trough (Fig. 19), reaffirming their igneous affinities. As before, t granophyres are removed from the trough towards the albite co of the diagram consistent with the replacement of potassium by sodium in these rocks. The extremely low calcium content of specimen 619, responsible for its position on the Ab - Or side is almost certainly in error in the analysis as its plagioclas oligoclase.

Trace element relationships.

The abundances of rubidium (13 to 393 p.p.m.), strontiur (63 to 549 p.p.m.) and Ba (132 to 924 p.p.m.) in the granites the Tennant Creek Complex in the Station Hill area are genera comparable to the concentrations of these elements in the qua feldspar porphyroids (Table 19) and are not abnormal for gran rocks (Hall, 1967b).

The same element ratios, as those considered for the qua feldspar porphyroids (Chapter 8), reveal that the red (phase granites and all of the phase C granites (with the exception specimen 619) are less fractionated than the main (phase A) member. The one representative sample of the phase B granite a trace element pattern similar to the main granite, whereas specimen 619 (phase C) is the only granite more fractionated the latter. In terms of these ratios, the main (phase A) gra appears more fractionated than the quartz-feldspar porphyroid. The $^K/Rb$ ratios, for example, are fairly low (135 to 167 for the main (phase A) granite and the subsequent phase B granite (147), while the red (phase A?) granite (164 to 213) l ratios closer to the average value for the continental crust and more typical of the quartz-feldspar porphyroids. The phas granites - the last representatives in the intrusive sequence are variable having $^K/Rb$ ratios with a range of 121 to 365 spa ing all the above values, the two most extreme values belongir to specimens 619 and 616 respectively.

Bearing in mind the limited number of $^K/Rb$ values availa for each granite phase, it is possible to suggest that the va phases do not show a simple sequence of either increasing or decreasing fractionation with order of intrusion (c.f. Hall, 1967b).

The $^K/Rb$ relationships of the main (phase A) granite are similar to those of the Cape Granites, South Africa considere by Kolbe and Taylor, (1966a) to be typically fractionated, hi level granites. These rocks do not show the values ($^K/Rb$ ave ing 100) indicative of abnormal rubidium enrichment recorded leucogranites from the Snowy Mountains, Australia (Kolbe and Taylor, 1966b) or those found in high-level granites in S.W. England (Bradshaw, 1967) and which may result from strong fra tionation during magmatic differentiation (Taylor, 1965).

The fact that the red granite has a different range of element ratios from the main (phase A) granite may indicate t the former is in fact a separate intrusive member rather than a variant of the main granite.

The $^{Th}/U$ ratios in the main (phase A) granite are close normal for granitic rocks.

<u>Origin of the mineralogy of the main (phase A) Station H granite</u>.

As already described, the main (phase A) member of the Station Hill Granite is "porphyritic", having prominent megac of potassium feldspar. Where the granite fabric is deformed, megacrysts tend to be suppressed by granulation along the foliation. However, the more massive fabrics suggest that t groundmass containing the potassium feldspar megacrsysts is a aggregate, mainly of quartz, plagioclase, biotite and minor potassium feldspar.

The recognition by many workers (e.g. Spencer, 1938; Rea 1957 and Stewart, 1959) that potassium feldspar developed in the inclusions and wall rocks (and also formed astride the contacts) of some granitic rocks, have no significant differe in composition from the potassium feldspar occurring in the granites, allows the possibility that the K-feldspars of the granites are a result of porphyroblastic growth in a solid medium. In many cases it is impossible to find any conclusiv evidence based on textural grounds for the mode of origin of the potassium feldspar grains.

In the Station Hill (phase A) granite, textural features of the plagioclase grains are consistent with formation under magmatic conditions. These are fine, oscillatory zoning with some of the grains showing coalescent features, as described the textural section, indicating an origin by synneusis in a melt (Vance and Gilbreath, 1967).

The quartz grains have shapes and embayments similar to those recorded in the porphyroidal rocks and common in high-l igneous rocks. From the discussion in Chapter 8, it is likel that the embayments were produced by magmatic corrosion rathe than amoeboid growth either as a phenocryst or a porphyroblas although in the absence of growth zones this cannot be defini established.

The restriction of the bulk composition of the granites the vicinity of the residual liquid composition in the experi tal system Q - Or - Ab - H_2O, is compatible with an origin in volving crystal-melt equilibria and hence the K-feldspar mega crysts (and, indeed, the other mineralogy) are considered to an integral part of that magmatic composition and are unlikel to have formed due to the metasomatic introduction of materia

This leaves the possibility that the K-feldspar megacrys originated due to post-magmatic redistribution of material, b such massive retexturing by porphyroblastic growth seems bare plausible as the megacrysts do not show evidence of having re- placed a pre-existing fabric. They do not contain inclusions with dimensions even approaching those of the groundmass mine (except for occasional euhedral plagioclase laths). The K-fel megacrysts do not possess xenomorphic rims rich in quartz ble which are featured by some authors (e.g. Wahl, 1925 and Mehne 1968) as evidence for a post-magmatic stage in the growth of megacrysts. In contrast, the K-feldspar grain edges are stra or curved and do not interlock with the grains of the coarse- to medium-grained groundmass.

These features suggest that the K-feldspar megacrysts ar phenocrysts rather than porphyroblasts. Whether the curved pe meters of many of the grains are due to magmatic corrosion or to some other process (Tuttle & Bowen, 1958) is unknown. The could record a preliminary stage of magmatic corrosion in whi curved edges are produced without breaching of the grain edge leading to embayments and internal corrosion which is thought to be the case with the K-feldspar megacrysts of the porphyro

The Carlsbad twins, with irregular composition surfaces, are compatible with twin patterns in igneous rocks, as mentio for the porphyroidal K-feldspars.

The orientation of euhedral plagioclase inclusions paral to the nearest crystal face of the K-feldspars has been accep by most authors (Frasl, 1954, Schermerhorn, 1956 and Hibbard, 1965) as a magmatic texture, although Smithson (1965) disagre However, although some euhedral andesine inclusions occur in relationship within the K-feldspar, they are not generally present in sufficient amount to be significant.

The thin, discontinuous mantles of andesine or oligoclas on some of the K-feldspar grains appear to be due to replaceme as the inner edge of the plagioclase rim is irregular in cont to the relatively smooth outer edge. The small runiform ande inclusions, which in some cases are indistinguishable from the intermittent mantles, may also be a product of replacement.

Vermicular quartz inclusions.

These small veinlets and irregular blebs of quartz have b described in potassium feldspar from granites (Popoff, 1928;

Terzaghi, 1940 and Mehnert, 1968) and two theories proposed i their origin. Popoff considered them to be primary as eutect intergrowths with the host feldspar, while Terzaghi believed them to be of replacement origin.

It may be appropriate to discuss the origin of the vermi cules in the light of their similarity in distribution and texture to the embayments and cavities typical of the potassi feldspar in the porphyroids.

In summary, both the embayments and cavities (Plates 4 t on the one hand and the vermicules (Plates 22 to 24) on the other, tend to have similar, sinuous shapes. Both occur in t core of the megacrysts as well as leading in from the grain perimeters. In distribution, both may show a vague, concentr zoning. They tend to follow the twin interfaces of composite grains and, in places, show a preferred orientation along cleavage traces of the host feldspar.

By way of contrast, while the vermicule edges are simila to those of the embayments and cavities, being composed of a combination of cusps convex towards the inclusions, the forme edges tend to be more intricate and irregular. A variety of minerals are included in the embayments and cavities, whereas the vermicules are composed only of quartz.

The similarity between the two textures suggests the pos bility that either the same process, or two different process leading to a convergence of texture was responsible for them.

Their orientation, distribution and shape infer a degree of structural control by the host potassium feldspar.

The origin of the quartz vermicules may be attributed to one of the following processes.

1. Resorption.

The vermicular shapes may have formed during magmatic resorption, the process considered responsible for the embaym and cavities in the porphyroidal K-feldspars and involving dissolution of the feldspar by a melt phase due to changes in physical conditions attendent upon movement of magma to highe levels in the crust. As already indicated, the quartz grain of the granite have embayments similar to those in the quartz of the porphyroids.

However, the fact that the vermicules are composed only quartz suggests that an origin involving magmatic resorption unlikely, as an acid, igneous melt phase would almost certain crystallize to a combination of mineral species. There is no evidence that the vermicules contained several mineral types and that post-magmatic processes removed all but quartz.

2. Replacement.

Origin of these textures by replacement of potassium feld spar by silica is consistent with their structural control by the host mineral and also with the mono-minerallic nature of vermicules. Replacement textures may be expected to be contr by zones of structural weakness in the host mineral giving unstable positions of slightly greater energy.

3. Cotectic crystallization.

That the quartz vermicules are due to cotectic intergrow is unlikely as the amount of quartz present in the potassium feldspar is never greater than about 5% by volume, which is v much smaller than the quartz content of cotectic or eutectic compositions (Mehnert, 1968). There is no evidence that the above mineral proportions have formed from their cotectic proportions by the replacement of quartz by potassium feldspar.

As indicated in the above discussion, the most likely origin of the quartz vermicules is by replacement of the host potassium feldspar of the granite. On the other hand, the embayments and cavities present in the potassium feldspar of t porphyroids appear to have developed by magmatic resorption. Hence, similar textural patterns are considered to result from the two different processes of resorption and replacement beca both of them appear to be controlled in an analogous fashion b the structure of the host K-feldspar.

Mineralogical features of the main (phase A) granite feldspars.

The potassium feldspars have similar albite (average 20 mol. %) and anorthite contents (Table 4 and Fig. 22) to those the quartz-feldspar porphyroids with the albite content being less variable in the granite feldspars. The plagioclases are of andesine composition in the least deformed rocks whereas i: the more foliated varieties they are oligoclase or andesine having altered in response to greenschist facies metamorphism with the fixation of the calcium as saussurite within the fel spar grains.

The compositional patterns of the feldspars, represented by two feldspar assemblages from the least deformed granite samples are plotted on Fig. 23 for comparison with those of th porphyroids. The present tie-line trends of those feldspars from the two environments are obviously different but it is considered (Chapter 8) that the porphyroidal feldspar pattern has been derived from one similar to the granitic pattern through alteration of the original andesine to albite. It is obvious that the feldspar compositional patterns of the more foliated granites are similar to the present porphyroidal patt due, in this case, to greenschist facies metamorphism.

As indicated in Chapter 8, even the feldspar assemblages present in the least deformed granites give submagmatic temperatures of formation (570 to 600^{o} C.) estimated by the two-feldspar geothermometer and infer that some sodium has escaped from the K-feldspar as a result of post consolidation processes. This appears to be a common feature of subsolvus granites and Hall (1967) has documented textural evidence for recrystallization in the form of small plagioclase grains on potassium feldspar grain boundaries. The thin incipient rims mainly of oligoclase, around some of the granite K-feldspar grains may be due to replacement of the K-feldspar by unmixed plagioclase during consolidation of the granite. As the plag: clase rims on the K-feldspars of the more deformed granite have been altered to albite and saussurite it follows that the must have been present prior to greenschist facies metamorphis

The K-feldspars compare closely with those of the porphyroids in terms of the rubidium, strontium and barium concen trations which show overlapping ranges (Table 4 and Fig. 22). On the average, the granite K-feldspars contain slightly more Rb (470 p.p.m.), almost similar Ba (3,300 p.p.m.) and a little less Sr (100 p.p.m.) than the respective amounts in the K-feld spars from the Warrego Porphyroid which are 335 p.p.m., 3,100 p.p.m. and 140 p.p.m.

As mentioned in Chapter 8, most of the element ratios of the granite K-feldspars (the exceptions are $^{Ba}/_{Sr}$ and $^{Ba}/_{K}$, Table 21) confirm the bulk rock patterns that the granite rati are less than the porphyroidal ratios (Figs. 21 and 23). The $^{K}/_{Rb}$ ratios of the granite K-feldspars average 240 (Table 21) compared with 254 found by Rhodes for K-feldspars from some Australian granites.

The plagioclases have normal contents of Ba and Sr (Tabl 7 and 8) for their andesine compositions (Heier, 1962). The distribution patterns of Ba and Sr between coexisting feldspa in the porphyroids and granites have already been discussed in Chapter 8. Although the plagioclase in some of the granit samples (specimens G and 621) has undergone "de-calcification" the products are preserved as saussurite in the grains and the Sr content does not appear to have been greatly altered as see by comparing the Sr values between those specimens having saussuritised plagioclase grains and those having unaltered grains (Table 8).

The structural state of the granite feldspars has already been compared with that of the porphyroidal feldspars. The K-feldspars in the granite are slightly more ordered (as indicated by the optic axial angles) than the porphyroidal K-feldspars and have maximum obliquities, the relatively narro range in obliquity indicating equilibrium with respect to that parameter. It is not known whether the maximum obliquities of the K-feldspars were conferred during the cooling phase of the igneous mass or during subsequent metamorphism.

The plagioclases in the granite have attained their high-order structural state either through slow cooling or during subsequent metamorphism.

Petrogenetic features of the megacryst-bearing enclaves.

As shown in Chapter 7, the compositions of the selected enclaves are rhyolitic and rhyodacitic corresponding to the leuc cratic and mesocratic varieties respectively.

Only the two rhyolitic enclaves with normative Q + Or + Ab greater than 80% are strictly eligible for consideration in the Q - Or - Ab - H_2O diagram where they occur in a position simila to most of the granites just inside the quartz field near the thermal minima for low water pressures (Fig. 19). Taking the C content into consideration, the rock compositions lie close to the low-temperature trough in the system Q - Or - Ab - An - H_2O

The composition of the two more basic representatives havi Q + Or + Ab less than 80% are not controlled by the low-tempera ture trough in either of the above systems.

Estimation of the water pressures of crystallization of the leucocratic rhyolitic enclaves (Fig. 19) taking the anorthi content into consideration are 500 to 1,500 bars but this is assuming no alteration of bulk compositions and not omitting th composition represented by the megacrysts.

The abundances of the trace elements Rb, Sr and Ba are within the ranges of their concentrations in the porphyroidal and granitic rocks (Tables 11 and 19). The Rb and Ba contents are greater and the Sr content smaller in the two leucocratic enclaves when compared to those of the mesocratic members.

All element ratios considered (except for $^{Ba}/K$) are greate in the two leucocratic enclaves. On this basis, the more acid rocks are less fractionated than the more intermediate represen tatives and, although the major element composition suggests that the rocks may be part of a differentiation series, the trace element ratios are not consistent with such a relationshi

The $^{K}/Rb$ ratios of the acid enclaves are in the range of those of the porphyroids while the $^{K}/Rb$ ratios of the more intermediate enclaves correspond to those of the main (phase A) granite (Fig. 21).

The conspicuous potassium feldspar, plagioclase and quartz megacrysts occurring in the enclaves always total less than 20% by volume and generally less than 10%. They are generally similar in size, shape and texture to those corresponding minerals in the host granite.

Hence, the plagioclase shows oscillatory zoning and synneu textures, features which indicate its magmatic origin. The quartz contains embayments and cavities which, as has been show are more likely to originate under magmatic than any other conditions. From these features, it follows that the megacryst of plagioclase and quartz have been derived from the same sourc as the fragmental groundmasses in which they lie and have not grown in the enclaves as porphyroblasts.

The K-feldspar megacrysts have no textures clearly indica of an origin either as phenocrysts or porphyroblasts. As the plagioclase and quartz grains appear to be of magmatic derivati it is considered likely that the potassium feldspar megacrysts are also. The Carlsbad twins recorded in the K-feldspar are nc inconsistent with such an origin. However, the evidence of origin is not conclusive.

Quartz vermicules similar to those in the granite K-feldsp are present in some grains but in more limited amount and are likewise considered to be of replacement origin. The almost ubiquitous mantles of andesine around the K-feldspar grains appear to be a product of the replacement of that mineral by th plagioclase as the outer edge of the mantle is smooth and regular, while the inner edge against the K-feldspar is irregul The chemistry of the replacement of K-feldspar by andesine requires that quartz be relinquished from the lattice of the former feldspar and the blebs of quartz confined to the plagioclase mantle is consistent with this relationship. Chess-board twin patterns in plagioclase are often associated with replacement (Starkey, 1959). In some grains, replacement has been complete and only plagioclase remains. In the event of the grains being of magmatic derivation it is possible that replacement of the K-feldspar megacrysts took place after incorporatio of the enclaves (and enclosed megacrysts) into the magma of the host granite.

The feldspar assemblages analysed from two of the mesocra
enclaves have compositional patterns similar to those of the host granites (Figs. 21 and 23) and infer temperatures of forma
tion of 540 to 600° C. estimated by the two-feldspar geothermo-
meter. The possibility of the loss of sodium from the K-feldsp
due to post-consolidation processes must also be considered he

With respect to trace element contents and ratios, the enclave K-feldspars have similar values to those of the granit
and porphyroidal rocks (Figs. 21, 22 and 23, Tables 4 and 21). Trace elements in the plagioclase were not investigated.

The structural states of the feldspars in the enclaves as deduced from optic axial angles and obliquities are identical t
those of the granitic feldspars (Figs. 25 and 26). As the plagioclase (and possibly the K-feldspar) are of volcanic origi
they will have undergone a more complex thermal history than th
feldspars from the porphyroids and granites with adequate opportunity for ordering having been reheated by the granite an
slowly cooled prior to the greenschist facies metamorphism.

RELATION AND COMPARISON OF THE GRANITES AND THE QUARTZ-FELDSPAR PORPHYROIDS.

It has been established that the two porphyroidal bodies studied in detail in this investigation - the Great Western Por-
phyroid (s.l.) and the Creek Bed Porphyroid - are fragmental py

clastics, the former being best interpreted as a thick, grossl conformable, possibly composite horizon of ash-flow origin and latter as a considerably smaller transgressive dyke or fissure filling. This raises the possibility that the other porphyroi occurrences recorded in the Tennant Creek area by Dünnet and Harding (1965) and Elliston (1965) are also pyroclastic in ori and is consistent with the interpretation, by the former autho of the Bernborough Formation as a composite pyroclastic horizo Two analyses of porphyroidal rocks from this formation in the vicinity of Bernborough are featured by Spry (1965) and are of rhyolitic character.

Other small bodies of rocks similar to the quartz-feldspa porphyroids have been recorded in the Tennant Creek area as dy stocks, vent-fillings and other small intrusions by Dunnet and Harding (1965) and Crohn and Oldershaw (1965). The confirmati of the high-level characteristics of the granites of the Tenna Creek Complex allows the interpretation that the Warramunga Gr rocks have been the focus of high-level igneous activity expre as granites, volcanics and various hypabyssal bodies such as d and fissure-and vent fillings. Hence, the acid igneous rocks are closely related in space and time (all being pre-tectonic the regional foliation caused by the phase 2 deformation) and the results contained in this investigation are at all represe tive, they are predominantly of calc-alkaline character.

It is probable that acid volcanism occurred throughout the deposition of the lower part of the Warramunga Group rocks inte calating with the shales and siltstones of the Warramunga Grour and producing much of the material for the volcanic greywackes and reworked pyroclastics which are characteristic of this association. Subsequently, granites intruded upwards through the volcanic-sedimentary sequences disrupting their own volcani and hypabyssals as recorded in the case of the Creek Bed Porphyroid and as inferred by the presence of fragmental rhyolitic and rhyodacitic enclaves in the main granite body at Station Hi

The rocks investigated in this study cover the different environments of the acid magmatisms - extrusives (the Great Western Porphyroid s.l.), hypabyssals (the Creek Bed Porphyroid and plutonics (the Station Hill Granites). It has been shown that on a petrographical, mineralogical and chemical basis, the rocks are so similar that they can only be interpreted as being genetically associated.

The constituent mineral grains of quartz, potassium feldspa and plagioclase are generally similar in size and shape (except where they have been fragmented by the extrusion of the porphyroids). Those of the porphyroids and enclaves are enclosed in recrystallized (the enclaves more than the porphyroids) fragment groundmasses while their counterparts in the main (phase A) gran combine to form a fabric not unlike that of high-level rapakivi granites with large potassium feldspar grains having incipient plagioclase rims and sometimes ovoidal shapes. However, a seco generation of quartz and feldspar typical of such granites is represented in minor amount in the main granite at Station Hil perhaps indicating that consolidation of the magma was in an advanced stage when a change in conditions produced a hiatus i the crystallization. The major element analyses of the main (phase A) granite indicate that it is not as potassium-rich as is often the case with typical rapakivis (Tuttle and Bowen, 19 however, any tendency for the rocks to have such a character could remain undetected due to the failure of the phase A gran rocks samples to entirely meet the grain size to weight specif cations proposed by Edelman (1962).

The quartz grains from all environments and the K-feldspa from the porphyroids have embayments and cavities considered t result from magmatic corrosion. The K-feldspars in the main (phase A) granite and enclaves have, in part, rounded edges wh may be the result of incipient magmatic corrosion.

All of the rocks are characterized by the subsolvus assemb lage potassium feldspar-andesine or its altered equivalent (potassium feldspar - albite) and the synneusis textures and oscillatory zoning in the andesine indicate that the rocks crystallized in that subsolvus (rather than hypersolvus) condit

Most of the rocks are similar to, or have been altered fr the compositions of residual acid liquids in the granite syster

(Tuttle and Bowen, 1958). However, trace element ratios have been used to examine the fractionation of the different rock associations. The fact that the unaltered quartz-feldspar porphyroids (and rhyolitic enclaves) are unfractionated ($^{K}/Rb$ ratios are close to the average value for the continental crus and that the subsequent main (phase A) and phase B granites ar mildly fractionated suggests increasing fractionation with tim However, this sequence is not followed by the red (phase A?) granites which have values more typical of the quartz-feldspar porphyroids or the subsequent minor (phase C) granite members which have a spread of $^{K}/Rb$ values, for example, spanning thos of the other rocks.

Andesine is the original composition of the plagioclase i the different environments although it has been altered to alb in the quartz-feldspar porphyroids probably by hydrothermal alt ation and to oligoclase or albite in some parts of the granite by greenschist facies metamorphism. The potassium feldspars in environments have a generally similar albite content but this is considered to be a result of post-magmatic and/or metamorphi recrystallization. No information is available on the primary albite content of the K-feldspars in any of the rock types.

The trace element abundances (Rb, Sr and Ba) and element ratios in the potassium feldspars from the different environmen have been shown to form a closely-related group within which tl feldspars show the same fractionation trends as found in their respective whole-rock compositions. For example, the K-feldsp from the porphyroids have on the average greater $^{K}/Rb$ ratios tl those of the K-feldspars in the main (phase A) granite. In element ratios, the enclave K-feldspars are more closely allied to either the granitic or porphyroidal values depending on the particular ratio.

Rhodes (1969) has shown that the Rb, Sr and Ba contents of potassium feldspars in granitic rocks depends mainly on the who rock compositions and also on the distribution coefficients of these elements between coexisting mineral phases. However, as such a large proportion of Rb, Sr and Ba are contained in the K-feldspars of granitic rocks, any variation in the concentrati of these elements associated with changes in the whole-rock compositions will be expressed in the content of these elements in the K-feldspars regardless of distribution coefficients.

In accordance, it is considered that the close similarity of the Rb, Sr and Ba concentrations and element ratios in the K-feldspars results from the generally similar abundances of th elements in the porphyroids, granite and enclaves due in turn t the similar major element composition of these host rocks.

The present distribution patterns of Sr and Ba between coexisting feldspars in the porphyroids and granites cannot be interpreted unambiguously due to the albitization of the andesi in the former rocks.

It is impossible to compare the original structural state of the feldspars in the different environments.

All plagioclases are in a highly-ordered structural state This is consistent with the post-magmatic effects (hydrotherma alteration, greenschist facies metamorphism and thermal metamorphism) which have variously affected the rocks. No informa is available on their structural states before they were affec by one or other of the above secondary processes.

The K-feldspars of the porphyroids appear to be in a slig lower-order condition than those of the granites and enclaves seen from the slightly lower values of 2V in the porphyroidal feldspars). This is consistent in the fixation of the order-disorder pattern at higher temperatures in the case of the porphyroidal K-feldspars compared to those of the granite and enclave. However, this is probably of little significance as the original order-disorder patterns would be expected to chang due to the various post magmatic processes. Also the disequili rium pattern in the obliquities of the K-feldspars from the Warrego Porphyroids may be due to secondary rather than magmati processes.

ORIGIN OF THE ACID MAGMA.

Consideration of the origin of the acid magma is outside the scope of this investigation and is rendered tentative, at best, due to the lack of reliable information concerning the distribution and character of the igneous rocks on a regional scale both in and beyond the Tennant Creek area. Nevertheles a few points appear relevant to this question.

According to Carmichael (1963), two-feldspar rhyolites (s as the quartz-feldspar porphyroids at Tennant Creek) may be pr duced by fusion of sialic material or fractional crystallizati of tholeiitic magma modified by sialic contamination and where intermediate (andesitic) rocks are largely absent, the rhyolit may have resulted from direct fusion. Only granitic rocks occ in any quantity in the Tennant Creek area (the Cabbage Gum Ign Complex in the south being of granodioritic character). Interm iate and basic rocks are of minor extent being limited to some dykes of gabbro, dolerite, diorite and lamprophyre in the Uppe Proterozoic and a thin development of intermediate and basic lavas in the Cambrian.

Hence, it would appear that the production of acid magma in this region may best be explained by direct fusion of sialic material. This appears consistent with the trace element ratic in the acid rocks in this investigation as none of them show st (except for one minor phase C granite sample) or abnormal fract ation which would be expected if the magma was derived by diffe entiation from a basic magma (Taylor et. al., 1956).

CHAPTER 10.

SUMMARY AND CONCLUSIONS.

The selected quartz-feldspar porphyroids studied in the Tennant Creek area - the Great Western Porphyroid (s.l.) and t Creek Bed Porphyroid - are of igneous origin being volcanic py clastics.

The primary megacryst assemblage is quartz, potassium fel spar and plagioclase (with a minor amount of a ferromagnesion mineral now pseudomorphed by biotite) or pseudomorphed equival Modal analysis indicates that, within the primary assemblage, individual mineral types are not present in striotly constant amount although they fall within relatively narrow limits.

The recrystallized groundmasses contain relict textures indicating the former presence of close-packed shards of volcan glass, perlitic crack patterns and possible amygdaloidal patche

The Great Western Porphyroid (s.l.) is made up of four po phyroidal occurrences - the Great Western Porphyroid (s.s.), th Black Eye Porphyroid, the Inset B Porphyroid and the Warrego Porphyroid - and is best considered as forming part of a grossl conformable, possibly composite, pyroclastic horizon whose sub-stantial extent, lack of bedding and original vitroclastic grou mass suggest an ash-flow origin possibly in a subaerial rather subaqueous environment. The contacts with the country rocks show no erosional features and are marked by zones of mutual contamination, the intimate nature of which infers that the roc were unconsolidated when intermixing occurred. The country ro in the Warrego area are crystal-vitric tuffs (quartz porphyroi and ash deposits which may in part be reworked pyroclastics and, along with volcanic greywackes, may form an essential par of the Great Western Porphyroid (s.l.).

The Creek Bed Porphyroid is substantially smaller than th Great Western Porphyroid (s.l.), is transgressive to the strat fication in the wall rocks and is considered to be a dyke or fissure-filling. The relict vitroclastic texture preserved in the recrystallized base infers, as in the case of the Great Western Porphyroid (s.l.), that the magma was in a fluidized condition. The contacts with the country rocks appear sharp suggesting that the wall rocks were consolidated at the time of intrusion.

Concerning the origin of the megacrysts of the quartz-feldspar porphyroids, the habits and twin patterns support an igneous derivation for these grains rather than an origin invol ing diagenetic or low-grade metamorphic recrystallization of th fragmental groundmasses of these volcanic pyroclastics. The compositions and structural states of the feldspars reflect formation or recrystallization at temperatures typical of green schist facies metamorphic rather than magmatic conditions and a considered to result from the post magmatic processes of hydro-thermal alteration and/or metamorphic recrystallization which h occurred in these rocks. The embayments and cavities developed in the K-feldspar and quartz of the porphyroids are considered be of magmatic origin and due to corrosion, although conclusiv proof is not available, rather than irregular growth and the c association between the curved edges and embayments suggests that the two are genetically connected and is consistent with weak corrosion of the euhedral grain habits resulting in round corners with associated, selective, internal corrosion produci embayments and cavities.

The compositions of the quartz-feldspar porphyroids are similar to those of calc-alkaline rhyolites except for a varia alkali ratio and a low CaO content. The failure of most of th compositions to plot in the position of residual liquids in th synthetic granite system is best explained by displacement of bulk rock compositions from that position as a consequence of secondary processes (most probably hydrothermal alteration) re- sulting in the redistribution of K, Na and Ca. This alteratio makes it impossible to realistically estimate the water pressu prevailing during crystallization of the magma which gave rise to the porphyroids. The bulk compositions of the porphyroids are distinct from their associated volcanic greywackes and ashes.

The compositional similarity of the quartz-feldspar porph roids and their association in space and time with the granite and selected enclaves of the Tennant Creek Complex (in the Sta Hill area), whose petrographical characteristics infers a high-level of intrusion in conformity with their position (prior to metamorphism) in unmetamorphosed Warramunga Group sediments, indicates that they are genetically connected and that the granites have reached their present position by intruding and disrupting their own volcanic and hypabyssal framework within the Warramunga Group sediments.

The major members of the granite complex have calc-alkali compositions and their relation to the synthetic granite syste suggests that they crystallized at water pressures in the rang 500 to 2,500 bars assuming the melts were saturated with water The megacryst-bearing enclaves in the main granite have coarse recrystallized vitroclastic groundmasses indicating that they volcanic pyroclastics, are of rhyolitic or rhyodacitic bulk composition and may have crystallized at water pressures of 50 to 1,500 bars.

In particular, the quartz-feldspar porphyroids have miner grains similar in size and habit to those of the main (phase A granite (and enclaves) whose texture has distinct similarities to that of rapakivi granites. Textural details suggest that t megacrysts of potassium feldspar, quartz and plagioclase in th main granite and enclaves are phenocrysts rather than porphyro- blasts. These K-feldspars have no embayments and cavities alt they have curved edges which may be due to incipient magmatic corrosion less severe than in the case of the porphyroidal K-feldspars.

The potassium feldspar-andesine assemblage is common to a environments indicating subsolvus crystallization. The andesi in some parts of the granite have de-calcified in response to greenschist facies metamorphism and few andesines have survive hydrothermal alteration in the porphyroids. There is some evidence that the potassium feldspar which is of generally sim albite content in the various environments may have lost some sodium either during cooling, hydrothermal alteration or meta-morphic recrystallization. Hence although andesine is in its unaltered condition (as seen from the oscillatory zoning), non of the potassium feldspars from the different environments can be considered unaltered.

Hence although it is certain that andesine is the origina composition of the plagioclase it is probable that the similar of the albite content in the K-feldspars from all environments is due to secondary processes and it remains unknown whether th primary compositions varied among the different environments.

While the similar albite content of the K-feldspars from the various environments appears to be due to secondary process the Rb, Sr and Ba concentrations are considered to form a close related group due to the similar amounts of these elements in t host rocks from the various environments which, itself, is a function of the similar major element compositions of these roc

The distribution of Ba between coexisting K-feldspars and plagioclase is no different in the granite and porphyroids.

However, the distribution of Sr is different but cannot be confidently accepted as a primary pattern because of the albit: tion of the andesine in the porphyroid.

The structural states of the feldspars from all environme: are in a highly-ordered condition and while the porphyroidal K-feldspars appear marginally less-ordered than those of the granite and enclaves (in terms of 2V) this cannot be interprete as a primary difference because of the presence of secondary processes which may alter the order-disorder patterns. The variable obliquity values reveal disequilibrium features in the K-feldspars of the Warrego Porphyroid.

In conclusion, secondary processes such as hydrothermal alteration and metamorphic recrystallization make it impossible to attempt to correlate primary order-disorder and compositiona features of the feldspars with different environments of occurr ences.

In terms of trace element ratios, the quartz-feldspar porphyroids are unfractionated while the main (phase A) granite of the Tennant Creek Complex is mildly fractionated. The vario members of the complex do not show a clear pattern of increasin or decreasing fractionation with sequence of intrusion and none of them (except one phase C member) show strong fractionation.

The two-feldspar mineralogy of the quartz-feldspar porphyroids, the absence of basic and intermediate igneous rocks and the fact that none of the main acid igneous rocks show strong o:

abnormal fractionation in trace element ratios infers that the magma originated by direct fusion of sialic material rather than differentiation from a basic magma.

APPENDIX

PETROGRAPHICAL METHODS.

I. (a) MODAL COUNTS OF MEGACRYST CONTENTS IN PORPHYROIDS.

(b) MODAL ANALYSES OF FOLIATED, PORPHYRITIC GRANITE.

(c) MOLECULAR NORMS.

MINERALOGICAL METHODS.

II. POTASSIUM FELDSPAR.

III. PLAGIOCLASE.

IV. MICA.

COMPOSITIONAL METHODS.

V. PREPARATION OF ROCK AND MINERAL SAMPLES FOR ANALYSES.

VI. X-RAY FLUORESCENCE SPECTROGRAPHY.

VII. FLAME PHOTOMETRY.

VIII. OTHER METHODS.

IX. EMISSION SPECTROGRAPHY.

PETROGRAPHICAL METHODS

1 (a) MODAL COUNTS OF MEGRACRYST CONTENTS IN PORPHYROIDS.

According to Hasofer (1963), the total or analytical erro in point counting, involving both counting and sampling error gives a variance (6^2) such that

$$6^2(p) \leq \frac{44pa^3}{RA}\left(1+5\cdot 8\left(\frac{R}{a}\right)^3\right)$$

where R is the grain radius, a is the grid spacing, A is the area counted and p is the percentage of the mineral present. This theoretical relationship has been tested by Solomon (1963) who states that calculated results are in close agreement with experimental values obtained by him and others on artificial models and natural rocks.

More recent work by Solomon and Green (1966) shows how it is possible to ensure a low to minimum variance by adjusting the relative values of R and a i.e. by choosing a grid with suitable spacing.

A value for the average radius of the grains of each mineral was estimated by measuring an appropriate number of grains.

Because of the different size ranges of the potassium feldspar, quartz and plagioclase, each mineral was counted on a grid with a spacing of 5mms., 4 mms. and 2mms. respectively The grids were ruled on perspex and then superimposed on cut and polished core specimens selected for analysis.

To test the validity of the counting conditions, replicate counts were carried out on specimen 61 and the experimental variances found for each mineral, the grids being moved between each count. The experimental variances were found to be smaller (see Table I) than those calculated from the above equation suggesting that the conditions are suitable.

In this way, maximum variances for each analysis (Table II) may be calculated from the counting conditions and may be used for statistical treatment of the modal data, without lengthy replicate measurements.

TABLE I

Modal analyses of megacrysts in porphyroids.

Repeated counts on specimen 61 (Warrego) - figures in volume percent.

count	potassium feldspar	quartz	plagioclase
1	19.1	10.4	9.7
2	18.7	10.1	9.2
3	19.5	9.8	9.4
4	20.3	8.6	8.9
5	19.4	10.5	9.7
6	17.1	9.7	-
7	18.4	8.6	-
8	18.1	10.7	-
9	20.0	9.9	-
10	17.6	9.8	-
Arithmetic mean	18.8	9.8	9.4
Variance	1.07	0.52	0.12
Variance (calc)	10.58	3.69	0.89

TABLE II

Maximum theoretical variances for megacryst counts.

	Megacryst %	Nos. of points	Variance	
Warrego				
51	13.2	918	4.30	k-feldsp
	11.3	1413	2.39	quartz
	6.0	5501	0.33	plagiocl
61	18.8	540	10.58	
	9.8	844	3.69	
	9.4	3248	0.89	
87	13.8	896	4.61	
	11.1	1305	2.54	
	3.6	1041	1.03	
401	12.6	1689	2.23	
	9.1	2591	1.05	
	10.4	4934	0.63	
94	14.7*	943	4.66	
	12.9	1478	2.61	
	13.2	5698	0.69	
249	19.6	342	18.20	
	-	-	-	
	-	-	-	
35	12.8	1037	3.69	
	16.4	1604	3.06	
	-	-	-	

* potassium feldspar replaced by plagioclase

TABLE II (contd)

	Megacryst %	Nos. of points	Variance
Warrego			
12	-	-	-
	13.3	1171	3.40
	-	-	-
Black Eye			
477	16.4	773	6.35
	9.1	1163	2.34
	9.3	2885	0.96
480	14.4	780	5.52
	9.8	1193	2.46
	7.5	2462	0.91
Creek Bed			
600	19.4	946	6.14
	12.6	1457	2.59
	13.0	3448	1.13
602	18.7	593	9.44
	13.0	902	4.31
	12.4	3541	1.05
606	16.0	412	11.62
	11.1	638	5.21
	14.1	2450	1.72

TABLE III

Statistical comparison of two pairs of modal analyses of Warrego quartz-feldspar prophyroids.

Specimens	Potassium feldspar	Quartz	Plagioclase	
61	18.8	9.8	9.4	$\bar{X}$
401	12.6	9.1	10.4	$\bar{X}$
$\lvert \bar{X}_1 - \bar{X}_2 \rvert$	6.2	0.7	1.0	
$\frac{\lvert \bar{X}_1 - \bar{X}_2 \rvert}{\text{standard error of difference}}$	43	10.1	50	

all differences are highly significant

Specimens				
61	18.8	9.8	9.4	$\bar{X}$
94	14.7	12.9	13.2	$\bar{X}$
$\lvert \bar{X}_1 - \bar{X}_2 \rvert$	4.1	3.1	3.8	
$\frac{\lvert \bar{X}_1 - \bar{X}_2 \rvert}{\text{standard error of difference}}$	26.1	39.5	193	

all differences are highly significant

1 (b) MODAL ANALYSES OF THE FOLIATED, PORPHYRITIC GRANITE

The accurate determination of the proportions of minerals present in a specimen becomes difficult if the rock is porphyritic, foliated and shows different degrees of granulation of the megacrysts causing a large variability in size and shape of the mineral grains (see Smithson (1963), Solomon (1963), Nesbitt (1964) and Barratt and Parslow (1966))

As a detailed, systematic survey of the granitic complex was not included in this study, a rigorous treatment of the mineral proportions present in the analysed granite specimens was not considered necessary.

In an attempt to classify the granites on a mineralogical basis, modal counts of the constituents quartz, potassium feldspar, plagioclase and others (mainly mafics) were carried out on cut slabs of rock using a square grid with a spacing of 5mms. ruled on perspex. Both the grid and the rock slabs were submerged in a water bath to eliminate spurious light reflections and improve definition.

The results are listed in Table IV along with the number of points counted and the area covered.

A comparison of the modal values with the normative amounts of the minerals calculated from the major element analyses is presented in Table V. The mode and mesonorm for each specimen should be reasonably comparable. The considerable differences demonstrated in Table V make the shortcomings of

TABLE IV

Approximate modal values of foliated, prophyritic Station Hill granite (values in volume percent).

Specimen	632	510/11	G	621
quartz	24.6	33.0	21.2	15.9
potassium* feldspar	36.8	38.5	50.6	45.7
plagioclase	17.4	16.6	15.7	16.1
mafics etc.	21.2	11.9	12.4	22.4
$\frac{\text{potassium feldspar}}{\text{total feldspar}}$ %	67.9	69.9	76.3	73.9
area counted (in square cms.)	378	257	313	358
number of points counted	1511	1029	1250	1431

* the albite in the perthite is included in the potassium feldspar total.

TABLE V

Comparison between approximate modal analyses (M) and the Barth mesonorms (N) for foliated, porphyritic Station Hill granite.

	632				510/11				G				621			
	M		N		M		N		M		N		M		N	
quartz	24.6		31.9		33.0		34.3		21.2		33.1		15.9		32.3	
potassium feldspar	36.8	54.2	22.6 24.3	54.9	38.5	55.1	28.0 25.2	57.8	50.6	66.3	29.6 26.0	59.8	45.7	61.8	27.8 26.0	58.9
plagio-clase	17.4		8.0 1.5		16.6		4.6 1.4		15.7		4.2 1.7		16.1		5.1 1.5*	
rest	21.2		11.8		11.9		6.5		12.4		5.3		22.4		7.3	

M in volume percent

N in molecular percent

* corundum

Figure I.

Classification of the Station Hill Granite (phase A) according to the modal values of quartz, potassium feldspar and plagioclase plotted on a diagram after Streckeisen (1967).

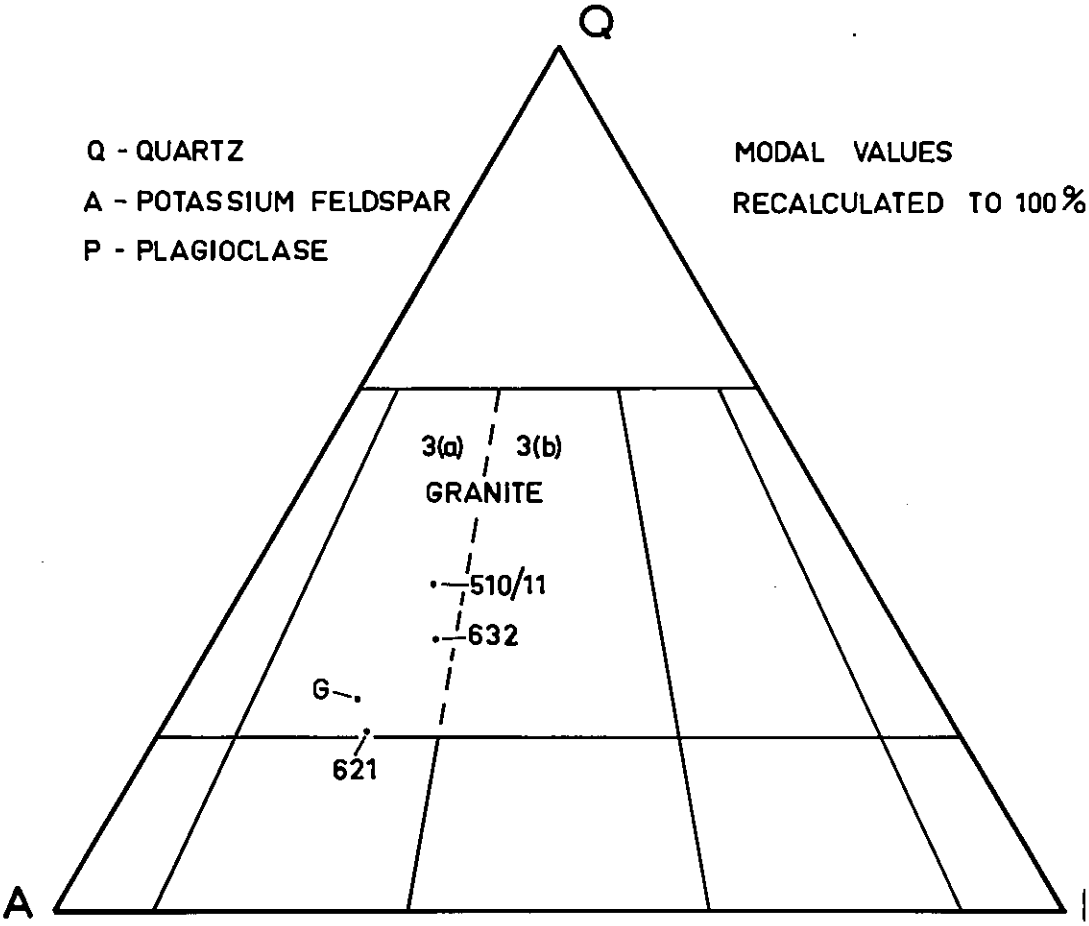


DIAGRAM AFTER STRECKEISEN (1967)

these modal values obvious even for classification purposes. The comparisons suggest that, in the modal counts, potassium feldspar and mafics have been overestimated whereas quartz and plagioclase have been consistently underestimated. This is probably due, at least in part, to

a) the use of only a single grid spacing for all minerals despite their different average grain sizes and despite the wide disparity in size of any one mineral species, and

b) the use of a macroscopic grid when part of the texture is so fine-grained that microscopic point counting is necessary.

1. (c) MOLECULAR NORMS

Epinorms are calculated following Barth (1955). The mesonorms are derived by the method of Barth (1959) except that the Ti is included in the biotite as the relatively high percentage of rutile, sphene or ilmenite does not seem warranted. Also it releases Ca resulting in a closer approach of the normative anorthite in the rock to the composition of the plagioclase grains determined optically. This treatment follows Hall (1966) as does the recalculation of the normative quartz and feldspars to weight percentages prior to plotting on the synthetic granite system of Tuttle and Bowen (1958).

MINERALOGICAL METHODS

II. POTASSIUM FELDSPAR

a) OPTICAL PROCEDURES.

Optic axial angle.

A 5-axes Leitz universal stage was used in the measurement of the optic axial angle (2Vx) in the thin sections of the potassium feldspar megacrysts. The orthoscopic procedure was employed as it was found easier to determine the diffuse extinction positions caused by the cross-hatched twinning and the strained mineral lattices, rather than use the interference figures obtained in the conoscopic technique (see also Marfunin, 1962, p.52).

The optic axial angle was measured directly in the sections of suitable orientation. In those megacrysts having the optic axial plane approximately parallel to the plane of the thin section, extinction procedures were adopted to measure the optic axial angle.

At first, 2Vx was calculated using the values of the appropriate extinction angles found by measurement on the univeral stage employing formula 2 of Joel and Muir (1964). However, this method was found to be time consuming and was discontinued as the extinction positions were too inaccurate to allow realistic use of the method. Accordingly, a simpler less accurate method was used in which the value of 2Vx was obtained by measuring one extinction angle and consulting a

Berek-Dodge chart (Noble, 1965).

Replicate measurements on the optic axial angle carried out on the same part of a potassium feldspar grain, using the orthoscopic procedure, determined the precision of the values as $\pm$ 2° (Table VI). The indirect method of measuring 2Vx is expected to be less precise.

Twinning

The orientations of the principal axes of the biaxial indicatrix and those of the cleavages and composition faces where possible were measured on a universal stage using the orthoscopic extinction procedure and plotted on a stereographic net.

Exact determination of the position of X, Y and Z and hence construction of the twin axis proved difficult as most grains have diffuse extinction positions due to straining in the lattices and to cross-hatched twin patterns.

As the composition surfaces are mainly irregular, they do not correspond to common crystallographic planes.

The angles between corresponding indicatrix axes in twin subindividuals were obtained from the stereographic net and as they are characteristic of the different twin laws, they allow identification of the twin. These angles are listed for the various megacrysts examined (Table VIII) along with the angular relationships of the {001} and {010} cleavages where observed. These values were compared with values obtained for

TABLE VI

Replicate measurements on the optic axial angle, 2Vx, of potassium feldspar and plagioclase using a 5- axes Leitz universal stage employing the orthoscopic procedure.

Potassium feldspar		Plagioclase	
Reading	$2Vx^{o}$	Reading	$2Vx^{o}$
1	76.8	1	99.6
2	80.8	2	99.0
3	77.4	3	99.2
4	78.6	4	98.6
5	76.6	5	97.8
6	77.2	6	97.8
7	80.6	7	97.8
8	78.8	8	99.4
9	79.4	9	97.4
10	78.0	10	97.8
Arithmetic mean	78.4	Arithmetic mean	98.4
Range	76.6 - 80.8 (4.2)	Range	97.4 - 99.6 (2.2)
Precision	$\pm 2^{o}$	Precision	$\pm 1^{o}$

TABLE VII

Means and standard deviations of optic axial angles (2Vx) of potassium feldspars from different rock types.

	$2Vx^{o}$		
Rock Type	Mean ($\bar{x}$)	Standard deviation	Number of measurements
Warrego Porphyroid	74.0	3.65	101
Black Eye Porphyroid	75.5	4.77	53
Station Hill Granite	82.3	3.45	65
Granite Enclaves	82.7	3.71	65

	Significance	
Tested	Standard error of difference	$\frac{\bar{x}_1 - \bar{x}_2}{\text{Standard error of difference}}$
Warrego-Black Eye	0.750	2.00
Granite-Granite Enclaves	0.628	0.64
Warrego-Granite	0.561	14.80

A difference of more than two standard errors between the samples means is regarded as probably significant, while a difference of three or more is considered to be highly significant (Moroney, 1958).

Table VIII.

Twin laws in potassium feldspar megacrysts from Tennant Creek.

POTASSIUM FELDSPAR TWINNING

Megacryst Number	Angles (in degrees)							Twin Law	Trace of Composition Surface
	$X \wedge X$	$Y \wedge Y$	$Z \wedge Z$	$\perp(001) \wedge \perp(001)$	$\perp(010) \wedge \perp(010)$	$\bar{Z} \wedge \perp(010)$	$\bar{Z} \wedge \perp(010)$		
Warrego									
90(c)	45	45½	3	46				Carlsbad	Irregular
329(a)	45	45	4					Carlsbad	Irregular
319	38	40	16	52				Carlsbad	Irregular
84(a)	15	73	71	88	88	14	10	Baveno	Irregular
Black Eye									
480(a)	43	43	1					Carlsbad	Relatively straight
480(c) 1	43	41	9					Carlsbad	Relatively straight
Mirarrmina									
8A(a)	17	77	74					Baveno	Irregular
8A(b)	6	6	3		8	6	6	*	Irregular
Creek Bed									
602(a)	43	42	8					Carlsbad	Irregular
Granite									
626(b)	38	38	6					Carlsbad	Irregular
621(a)	50	50	4			5½	4	Carlsbad	Relatively straight
621(b)	57	75	64					?	Irregular
631(b)	39	38½	5½	52				Carlsbad	Irregular
Granite Enclave									
511	6	4	4	8				*	Relatively straight
629(c) 1	40	40	7½	51			23	Carlsbad	Relatively straight
514	3½	4	4½	11	3½	7	7	*	Irregular
630(a)	37½	37½	5				12	Carlsbad	Irregular
519(a)	43	44½	12					Carlsbad	Irregular

different twin laws prepared by performing twin transformations on potassium feldspar in Marfunin (1962, fig.44 and 1961, fig.8) and Emmons (1959, Plate 12).

The departure from monoclinic symmetry is evident in the values for the angle $Z \wedge \perp(010)$ which ranges from 4-23°.

In view of the difficulties mentioned above in determining the orientation of the indicatrix axes and the uncertainty in measuring the attitude of the cleavages from slides of ordinary thickness (see Marfunin 1962, p.56), these angles must be regarded as approximate.

Refractive index

The refractive index (Nx) was measured on suitably orientated mineral grains immersed in calibrated standard refractive index oils using the Becke line effect with a sodium light source. As Y is nearly perpendicular to face (001), X and Z effectively lie in the $\{001\}$ cleavage. Mineral grains lying on this cleavage can be identified by their shape and by the fact that they show the clearest development of cross-hatch twin patterns.

The values are presented in Table IX.

TABLE IX

Refractive index, Nx, of some analysed potassium feldspars.

Specimen	Nx ($\pm$0.001)	Location
2	1.522	Warrego porphyroid
5	1.520	Warrego porphyroid
51	1.520	Warrego porphyroid
479	1.520	Black Eye porphyroid
632	1.520	Station Hill granite
510/11	1.522	Station Hill granite
519	1.520	Enclave in Station Hill granite

b). X-RAY PROCEDURES.

Obliquity.

The powdered K-feldspar specimens were x-rayed on a Phillips diffractometer using cavity mounts. Instrument conditions included CuK_{α} radiation at 40kV and 20mA at a scanning speed of $1/8^{o}$ 2θ/min. using a 1^{o} slit. The diffractograms recorded values of 2θ from 22 to 24^{o} and from 29 to 31.5^{o} and demonstrated the splitting of the x-ray spectra III and I$\bar{I}$I, 130 and 1$\bar{3}$0 and 131 and 1$\bar{3}$1.

The obliquity (Δ - value) of the K-feldspar is obtained from the separation of the spectra 131 and 1$\bar{3}$1 followin Goldsmith and Laves (1954). The relationship is conventionally expressed in the following manner :

$$\Delta = 12.5 \quad (d_{131} - d_{1\bar{3}1})$$

No internal standard is required as the function is derived from the separation of two spectra. The precision of the method found from replicate scans is $\pm$ 0.02.

Composition

The proportion of albite (Ab + An) present in solid solution in the K-feldspar lattice influences the spacing of the $\bar{2}$01 lattice planes and may be measured by accurately recording the position of the $\bar{2}$01 x-ray reflection (Orville, 1967). The position of that reflection is expressed in Orville's graph, relative to the 101 x-ray reflection of $KBrO_3$, which occurs at $2\theta = 20.205$ ($\pm$ 0.010) for CuK_{α} radiatio at $10^{o}C$. Consequently, potassium bromate is used as an

TABLE X

Variation in obliquity, Δ , within single hand specimens.

Warrego Porphyroid

Specimen 60		Specimen 255	
Megacryst	Δ	Megacryst	Δ
1	0.84	1	0 - 0.85
2	0.86	2	0 - 0.88
3	0.80	3	0 - 0.94
4	0.80	4	0 - 0.89
5	0.86	5	0 - 0.88
6	0.85	6	0 - 0.85
7	0.89	7	0 - 0.89
8	0.84	8	0 - 0.88
9	0.86	9	0 - 0.90
10	0.86	10	0 - 0.91
Arithmetic mean	0.85	Arithmetic mean	0 - 0.89
Range	0.80 - 0.89 (0.09)	Range	0.85 - 0.94 (0.09)
heated	0.80	heated	0.81

Black Eye Porphyroid

Specimen 480

Megacryst	Δ
1	0.91
2	0.90
3	0.89
4	0.89

TABLE X contd.

Black Eye Porphyroid

Arithmetic mean 0.90

Range 0.89 - 0.91 (0.02)

Station Hill

Granite		Granite enclave	
Specimen 626		Specimen 519	
Megacryst	Δ	Megacryst	Δ
1	0.93	1	0.89
2	0.91	2	0.85
3	0.90	3	0.93
4	0.89	4	0.93
5	0.89	5	0.88
6	0.93	6	0.95
7	0.90	7	0.91
8	0.90	8	0.90
9	0.91	9	0.85
10	0.95		
Arithmetic mean	0.91	Arithmetic mean	0.90
Range	0.89 - 0.95 (0.06)	Range	0.85 - 0.95 (0.10)
heated	0.84		

Precision of the method found from replicate scans is $\pm$ 0.02

TABLE XI

Comparison of potassium feldspar bulk compositions, analysed by two X-ray methods, averaged within each rock type.

	Column 1 X-ray diffraction Ab + An mol. %	Column 2 X-ray fluorescence Ab + An mol. %
Warrego	13.9†	18.1
	R(3.7-22.5) D 4.9	R(12.6-24.3) D 5.1
Black Eye	16.9	15.0
	R(13.5-20.2) D 2.3	R(13.4-16.1) D 1.5
Granite	22.3	21.2
	R(15.7-29.0) D 4.0	R(19.1-22.3) D 1.5
Enclave	19.7*	20.7
	R(16.2-26.0) D 3.1	R(17.3-24.1) D 4.8

† in calculating this total, the Group 3 megacrysts were referred to Orville's curve for monoclinic feldspars rather than the triclinic feldspar curve as used in Fig. 10 and Table 3.

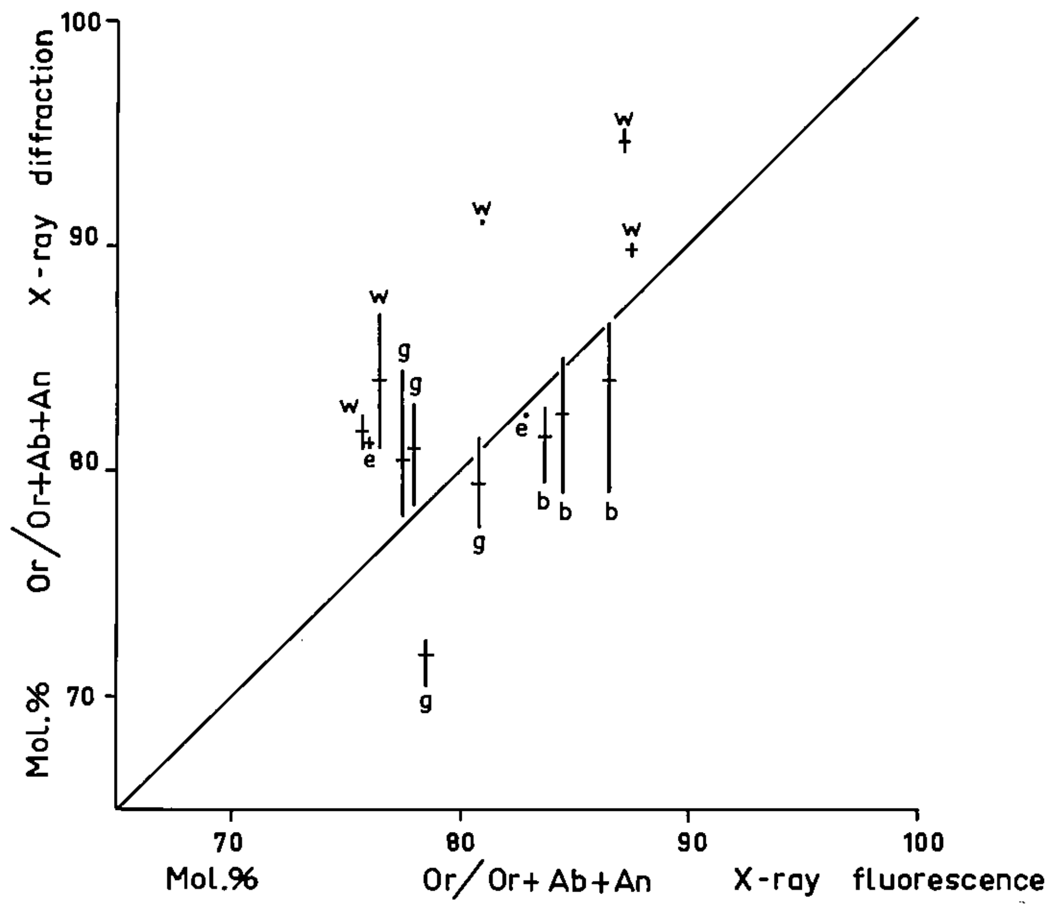
* neglecting megacrysts with extensive plagioclase rims

R-range in values

D-standard deviation of values.

Figure II.

Graphical comparison of the bulk composition of some potassium feldspars determined by two X-ray methods (each plot representing the feldspar from an individual rock specimen).



w – Warrego b – Black Eye

g – granite e – granite enclave

Graphical comparison of the bulk compositi
of some potassium feldspars determined
two x – ray methods

internal standard.

Each K-feldspar specimen was mixed with potassium bromate and smear mounts prepared using vaseline were x-rayed on a Phillips diffractometer, using CuK$_\alpha$ radiation (40kV and 20mA) at a scanning speed of 1/8° 2θ/min.

Replicate scans give the precision of the method as $\pm$ I.0 mol. % (Ab + An).

III. PLAGIOCLASE

The composition and structural state of plagioclase was investigated by both optical and x-ray methods.

Depending on the composition of plagioclase, certain methods are more sensitive than others in defining the structural state. In the albite-rich (Ano-40) composition range, X-ray diffraction methods and optic angle determinations are most effective (Slemmons, 1962b); whereas the orientation of the optic indicatrix relative to an easily identifiable crystallographic orientation, normally an (010) composition surface, is less sensitive although still useful.

The optical and X-ray measurements reflect the extent of order or disorder in the lattice-structure of the plagioclase. Although these order-disorder relationships are commonly referred to the order-disorder variations of Si and Al atoms, (Slemmons, 1962a; Deer, Howie and Zussman 1963 and Noble 1966) several different types of ordering or combinations of types are possible (Megaw 1959), none of which are distinguishable by these particular measurements.

(a) <u>OPTICAL PROCEDURES</u>

<u>Orientation of the optical indicatrix</u>.

In the initial stage of the investigation, the Warrego and Black Eye plagioclases were measured using a 5 - axes universal stage technique outlined by Noble (1965). This involved the determination of the attitude of two of the principal axes of the optical indicatrix, $|X$ and $|Y$, relative to the crystallographic planes (010) and (001). Using this technique, the plots are recorded directly onto rectangular charts without resort to the construction necessary in the 3- or 4- axes universal stage technique of Slemmons (1962a).

In Figs 7 (a) and (b), the parameters $|\Delta A_2|_x$ and $|\Delta A_2|_y$ are functions of the angles $X^\wedge\perp(010)$ and $Y^\wedge\perp(010)$ respectively (see Noble, 1965). The charts are based on Table 3 of Slemmons (1962a). Slemmons' data is in turn based on measurements of plagioclases of Smith and Yoder (1956). The resulting curves are considered by Slemmons not to differ markedly from those of Kohler (1942), van der Kaaden (1951) or Burri (1956).

An advantage of this procedure over that of Slemmons' is that it is unnecessary to first identify the twin-law before plotting on the charts. The recognition of the twin-law can often be difficult, particularly in the albite composition range where $|X$ is parallel, or at a small angle to (010).

The direct method used here can be applied to all twins having (010) as the composition plane or indeed all plagioclase crystals with a clearly recognisable (010) cleavage. However, according to Noble (1965), the composition surfaces of albite are preferable as they tend to be more regular than those of Carlsbad or albite-Carlsbad twins.

An (010) composition plane or cleavage is identified by first making its perpendicular horizontal and then rotating the plane around it. In all positions the plane will show negative elongation, except for anorthite-rich compositions, i.e., it will be length fast as Z is approximately perpendicular to it.

The plagioclase samples in Fig. 7 show a spread on either side of the high-order curves, some readings reaching halfway to the low-order curves.

As seen from the more sensitive optic axial angle values this scatter which, in the case of Fig. 7 (a), is symmetrical on either side of the curve, must represent errors in measurement rather than a range of intermediate structural states or external optical-crystallographic scatter as defined by Vogel (1964). The spread of points appears to be due to :

(a) the errors involved in orientating the optical indicatrices and composition planes, and possibly

(b) the fact that the composition planes might deviate from 'ideal' crystallographic directions (Tobi, (1965).

Whereas in Figs. 7 (a) and (b) the two curves lie 5^{o} apart in Fig. 7 (c) using (001) cleavage a maximum departure of 15^{o} can be realised in the albite composition range. However, although Fig. 7 (c) appears to be more sensitive than the other diagrams, its importance is reduced by the greater difficulty of recording accurately the orientation of the (001) cleavage as demonstrated by the greater spread of points along the ordinate of over 10^0 in the case of Fig. 7 (c) as against approximately 5^o in Fig. 7 (a).

In the later part of the investigation, when available, the method of Rittmann and El-Hinnawi (1961) was employed in the determination of the plagioclases in the Creek Bed porphyroid, the granites and granite enclaves. This technique is a modification of the Rittmann zone method which now allows the rapid distinction between ordered and disordered structural states.

Optic axial angle

In the course of the above manipulations on the universal stage, the optic axial angles of the plagioclases were measured using the orthoscopic extinction method.

Refractive Index

The refractive index measurements were carried out on the crush fragments of several plagioclase grains, or of fused plagioclase quenched to a glass, immersed in calibrated refractive index oils by observing the Becke line effect in sodium light.

Compositions were found from the curves of Smith (1958) and Foster (1955).

(b) X-RAY PROCEDURES

The X-ray powder diffraction method involves the measurement of the separation of certain critical peaks, sensitive to the extent of order-disorder in the plagioclase lattice.

In the sodic plagioclase range of composition, the separation of the two reflections (131) and $(1\bar{3}1)$ is one of the most commonly used peak intervals (Smith and Yoder, 1956). However, according to Smith (1956), where the albites are peristerites they have an adverse affect particularly on the position and resolution of the peak $(1\bar{3}1)$ and hence it is more accurate to measure the separation of peaks $(\bar{1}32)$ and (131).

Both functions are recorded in Fig. 9 , there being no significant difference in result.

IV. M I C A

The optic axial angles of the micas were measured in thin sections on a universal stage using the conoscopic procedure in sodium light.

The X-ray patterns were obtained from hand-picked mica flakes, subsequently powdered and exposed in a Phillips diffractometer, using CuK_{α} radiation (40kV and 20mA) at a scanning speed of $\frac{1}{2}^{o}$ 2θ / min. In both occurrences, kaolinite peaks were detected and confirmed by their disappearance on heating to just above $600^{o}C$.

COMPOSITIONAL METHODS

V. PREPARATION OF ROCK AND MINERAL SAMPLES FOR ANALYSIS.

Rock samples were reduced in size initially between the jaws of a hydraulic rock splitter and then further reduced int small chips and flakes by treatment on a hard steel boss with a hard steel hammer. The material was then reduced to powder in the chrome-steel head of a vibratory swing mill.

The rock powder prepared by this method easily passes through a 120-mesh sieve and, as the rocks were analysed in duplicate, the small quantities used in the analyses are expected to be representative of the bulk sample (Kleeman, 1967).

In quantity of material treated, most of the rocks approa the grainsize to weight specifications proposed by Edelman (1962) to ensure that each analysis represents its appropriate rock mass. However, in the case of the excessively coarse-grained, porphyritic granites, insufficient material was available to reach the suggested limit and the four analyses of this rock are not claimed to be undeniably representative of the rock mass. Nevertheless, it is considered that the analyses are more than adequate to illustrate the compositional characteristics of the granite type.

Finally, the powder sample of each rock was moved around (one hundred times) on a large sheet of tracing paper in an attempt to ensure that the successive portions from the swing mill were thoroughly mixed together into a homogeneous bulk sample.

The mineral samples of potassium feldspar and plagioclase were hand-picked from those parts of the analysed rock specimens which were not powdered for bulk analysis.

Before final powdering of the potassium feldspars for analysis, the crushed fragments were sieved and an attempt was made to purify the 100 - 150 mesh fraction, using a Cook isodynamic magnetic separator to eliminate the biotite and chlorite inclusions and heavy liquids (tetrabromoethane diluted with acetone) to remove the plagioclase and quartz inclusions.

Finally, the purified fractions of potassium feldspar were powdered in a similar manner to the rock samples.

The 100 - 150 mesh fraction will yield grain fragments in the size range 0.10 to 0.15 mm. These fragments are several times larger than the average size of the plagioclase present in perthitic relationship and are therefore expected to be representative of the bulk composition of the potassium feldspar (i.e. K-feldspar plus perthitic plagioclase).

Most of the infrequent plagioclase having dimensions at least several times greater than 0.10 - 0.15 mms. will be represented as individual grains in the mesh fraction and will therefore be excluded in the subsequent heavy liquid treatment of the feldspar separates.

The patch and vein plagioclase in the porphyroidal K-feldspars, the mantle plagioclase and the large euhedral plagioclase in the granite and enclave K-feldspars fall into this category. This is in order for there is little possibility of explaining their origin by exsolution from the K-feldspar as in the case of the relatively fine-grained perthitic plagioclase.

The small plagioclase inclusions, which may be associated with mantle plagioclase, will not be eliminated from the K-feldspar separates and will unavoidably feature in the bulk composition despite the fact that they may be of replacement rather than exsolution origin.

VI X-RAY FLUORESCENCE SPECTROGRAPHY

An X-ray fluorescence technique following the method of Norrish and Chappell (1967) was used in the determination of SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, K_2O and P_2O_5 in the rock and feldspar samples. Only the rock samples were analyse in duplicate.

The ignited powdered samples were dissolved in a borate fusion mixture prepared by mixing 38.0 gms. anhydrous lithium tetraborate, 29.6 gms. lithium carbonate and 13.2 gms. of lanthanum oxide and fused in gold-plated platinum crucibles at approximately 1000°C. Each powdered sample of 0.56 gms. weight was added to 3 gms. of borate mix and 0.04 gms. of sodium nitrate, the latter to ensure oxidising conditions during fusion. The melt was then poured and quenched on a carbon-coated aluminium block, using an aluminium plunger with the production of a flat glass disc of standard size. The lanthanum oxide is included in the borate mix as a heavy absorber to reduce matrix effects in the glass discs.

The glass discs were analysed in a Phillips vacuum X-ray spectrograph (PW 1540) using pulse-height selection and employing the conditions listed in Table XII.

Artificial standards were used throughout the determinati and the standard rocks WI, GA, GH and BR were included as a check on the reliability of the artificial standards and the conditions of the determinations. After the nominal (apparent percentages of the elements and been determined, absorption corrections were applied (by means of a computer programme) to each element to allow for the matrix effects of the other elements in each glass disc.

The precision for the major element analyses expressed as the relative deviation (c) is given for average concentrations of the elements in Table XII. The relative deviations are calculated from duplicate analyses in the manner indicated for calculating the precision of the trace element data.

The trace elements Rb, Sr, Ba, Th and U were determined on briquetted powder samples supported on the back and edges by boric acid. These pressed pills were analysed on the X-ray spectrograph under the conditions listed in Table XIII. Approximately 2 gms. of powder were used, thus fulfilling the condition of "infinite thickness".

Artificial standards made up with kaolin were used with the standard rocks WI, GI, TI and BR (rocks GMI - 13, EU2 - 8 and JAI - 5 of Kolbe and Taylor, 1966 served as standards for Th and U) allowing a check on the validity of the measuring conditions. The matrix corrections were calculated by computer from the known major element compositions of the powders.

The precision of the results was calculated from duplicate analyses as the relative deviation (c) where

$$c = \pm\sqrt{\frac{\Sigma d^2}{n-1}}$$

and d is the percentage deviation of each measurement from the

TABLE XII

Analytical conditions for major elements in X-ray fluorescence spectrography.

Element	Tube	Crystal	Counter	Counting time in Seconds	Precision (c) at average concentrations
Si	Cr	P.E.	Flow	96	0.8 (73.0%)
Al	Cr	P.E.	Flow	96	1.1 (13.5%)
Fe	Cr	LiF_{220}	Scint.	96	1.4 (3.1%)
Mn	Au	LiF_{220}	Scint.	96	66 (0.03%)
Mg	Cr	A.D.P.	Flow	96	2.5 (0.6%)
Ca	Cr	LiF_{220}	Flow	96	6.5 (0.9%)
K	Cr	P.E.	Flow	96	0.8 (5.2%)
Ti	Cr	LiF_{220}	Scint.	96	2.6 (0.4%)
P	Cr	Ge	Flow	96	1.2 (0.7%)

K lines were used in all cases

TABLE XIII

Analytical conditions for trace elements in X-ray fluorescence spectrography.

Element	Tube	Crystal	Counter	Counting (secs)	Spectral line	Detection limit p.p.m.	Precision (c)
Rb	Mo	LiF_{220}	Scint.	96	$K\alpha_1$	1	4
Sr	Mo	LiF_{220}	Scint.	96	$K\alpha_1$	1	3.5
Ba	Cr	LiF_{220}	Flow.	96	$L\beta_2$	15	3.5
Th	Mo	LiF_{220}	Scint.	96	$L\alpha_1$	3	-
U	Au	LiF_{200}	Scint.	96	$K\alpha_1$	3	-

arithmetic mean of each pair of duplicates and n is the number of duplicate determinations.

The limit of detection was calculated as equal to

$$\frac{1}{n}\sqrt{\frac{Rb}{t}}$$

where n = counts per second per p.p.m.

Rb = background count rate.

t = analytical time on peak + background.

VII. FLAME PHOTOMETRY

Sodium was determined on the dried rock and mineral powders (the potassium values arrived at by the X-ray fluorescence techniques were also checked) on two different flame photometers employed at different stages of the work. The instruments used were an OPTICA CF4 spectrophotometer with a flame photometer attachment and an EEL flame photometer.

The powders were dissolved in 40 per cent HF and I:I H_2SO_4 then evaporated to a syrupy residue in teflon beakers on a water bath. The residue was brought into solution with deionized water plus about 10 mls. concentrated HC1. The resulting solutions were made up to 250 mls. in standard volumetric flasks and stored in polythene bottles prior to measurement on the flame photometer. Standard curves were established using artificially prepared solutions and, during each series of measurements, solutions of the standard rocks WI, BR, GA and GH were included to check on the reliability of the determinations.

VIII. OTHER METHODS

H_2O^- was calculated from the weight loss on powders dried overnight at 110° C. while ignition losses were recorded on powders heated at 1000° C. for one hour in a furnace.

Ferrous iron was determined according to the titration method of Reichen and Fahey (1962).

IX. EMISSION SPECTROGRAPHY

The concentration of strontium and barium in plagioclase (and some potassium feldspars) were determined by an emission spectrographic technique similar to that of Kolbe and Taylor (1966) as the quantities of powder available were not sufficient to allow the use of the X-ray fluorescence method already outlined.

The instrument employed was a Jarrell-Ash (model 7I-100) grating spectrograph having a 15,000 lines per inch grating in the first order. Samples were diluted with graphite powder containing palladium for use as an internal standard and arced to completion. Determinations were made at least in duplicate and the standards used were rocks WI, AGV, G-2 and TI and the feldspar NBS 99. The lines measured were strontium at 4607 Å, barium at 4934 Å and palladium at 3421 Å.

The precision of the data calculated from duplicate analyses in the same manner as the X-ray spectrographic data is $\pm$ 6 and $\pm$ 3.5 for strontium and barium respectively.

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